1.5-GeV Proton FFAG as Injector to the BNL-AGS

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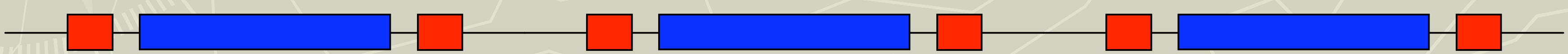
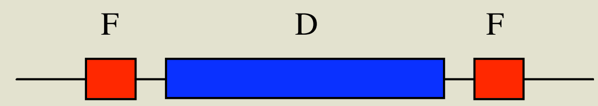
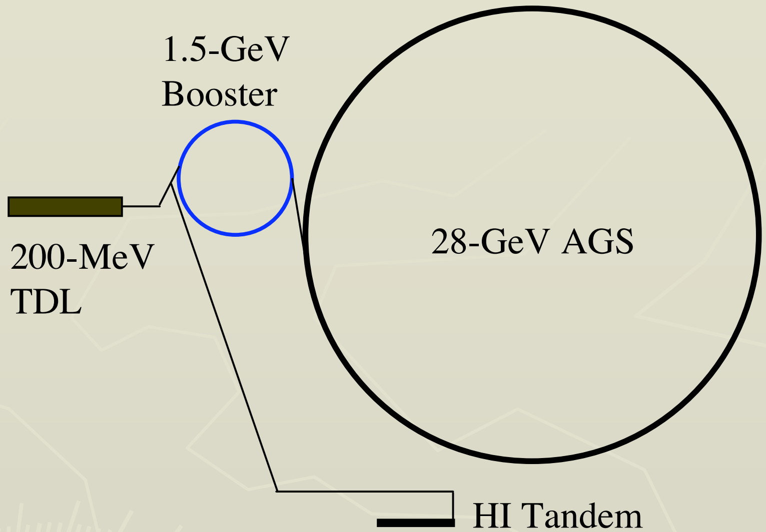


Present BNL - AGS Facility

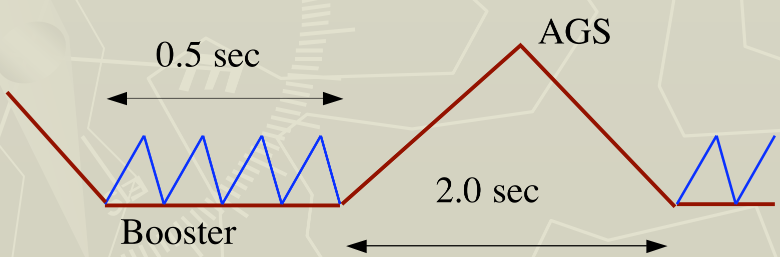




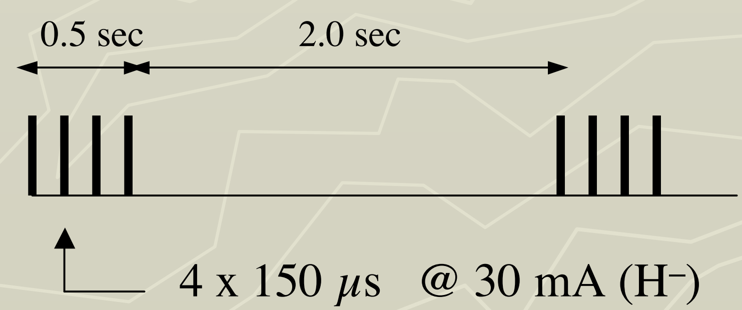
Performance

Rep. Rate	0.4 Hz
Top Energy	28 GeV
Intensity	7 x 10^{13} ppp
Ave. Power	**125 kW**

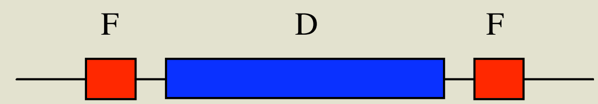
Typical AGS cycle for Protons



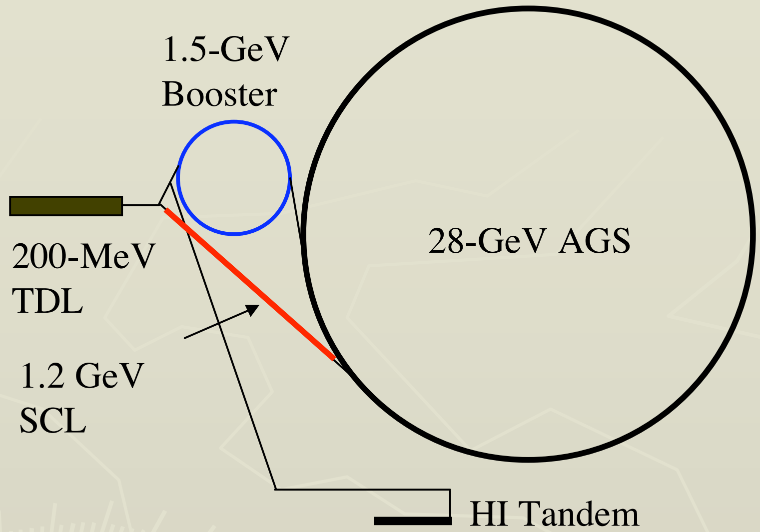
Typical DTL cycle for Protons



AGS Upgrade with 1.2-GeV SCL



C-A/AP/151

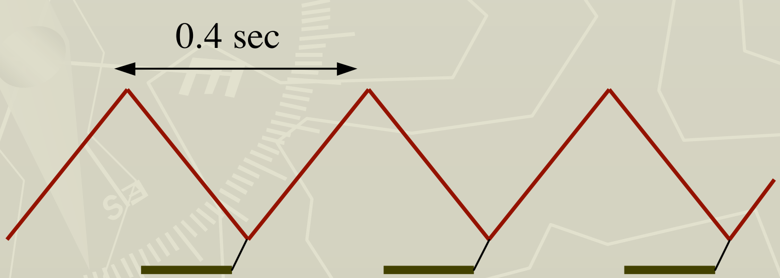


Performance

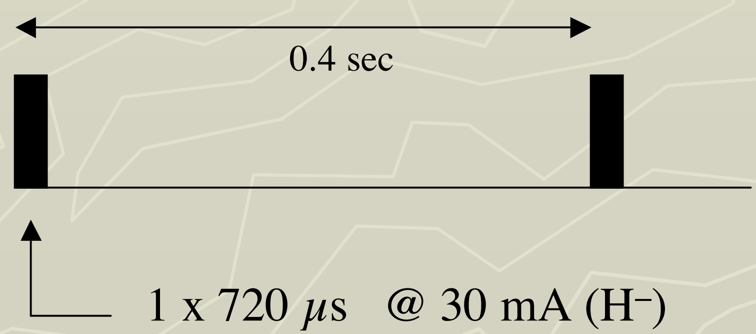
Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	10 x 10^{13} ppp
Ave. Power	**1.0 MW**

Only Protons, **no** HI

AGS Cycle with 1.2-GeV SCL

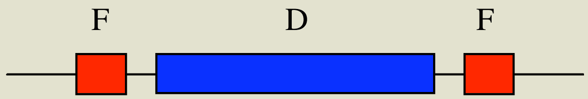


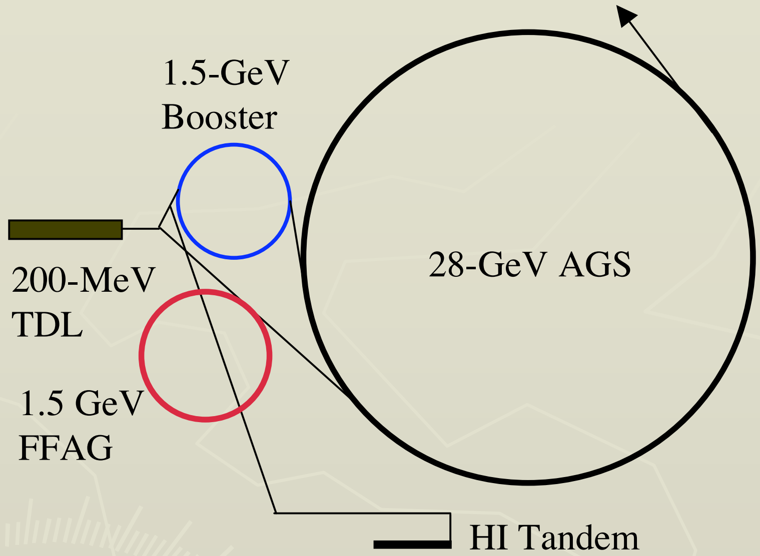
Typical DTL cycle for Protons



AGS Upgrade with 1.5-GeV FFAG

C-A/AP/138



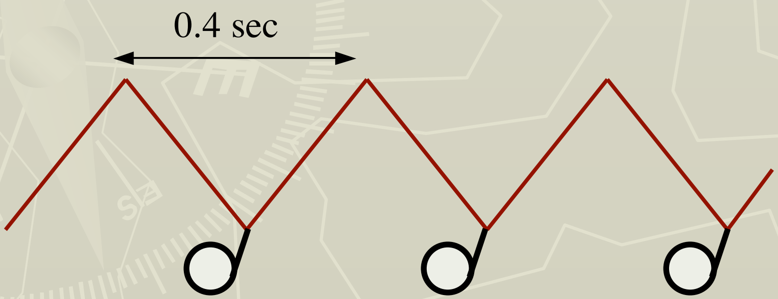


Performance

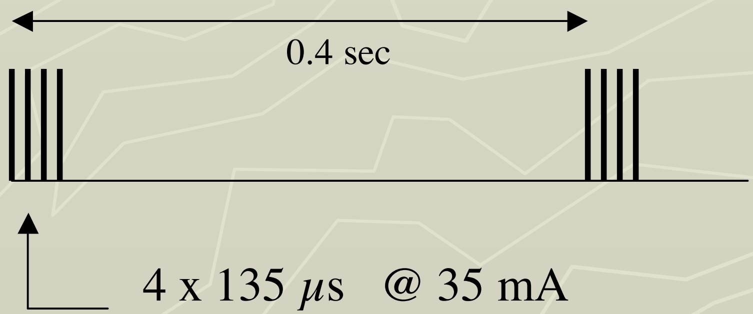
Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	10 x 10^{13} ppp
Ave. Power	**1.0 MW**

Protons, **and** HI

AGS Cycle with 1.5-GeV FFAG



Typical DTL cycle for Protons



4 x 135 μs @ 35 mA
1.5 ms apart (total 5 ms)

1.5-GeV AGS FFAG

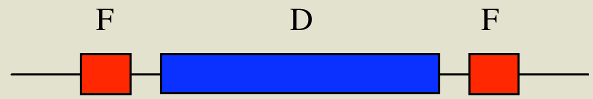
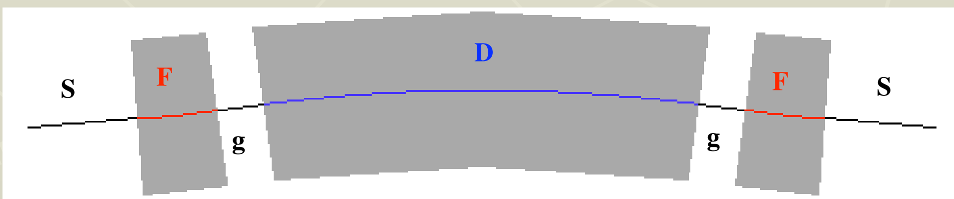


Table 1. Proton Beam Kinematic Parameters

	Injection	Central	Extract.
Kinetic Energy, MeV	**200**	**786.722**	**1,500**
β	0.5662	0.8391	0.9230
γ	1.213	1.838	2.599
Momentum, MeV/c	644.4	1,447	2,250
Magnetic Rigidity, kG-m	21.496	48.283	75.069
$\Delta p/p$	**–0.5548**	0.0	**0.5548**

Table 3. The AGS-FFAG Parameters for the Reference Trajectory

Circumference	244.439 m
Number of Periods	42
Period Length	5.81998 m
Short Drift, g	0.30 m
Long Drift, S	1.405954 m
Phase Advance / Period, H/V	97.7142° / 97.7142°
Betatron Tunes, H/V	11.40 / 11.40
Transition Energy, γ_T	39.7573 i



Non-Scaling FDF Triplet

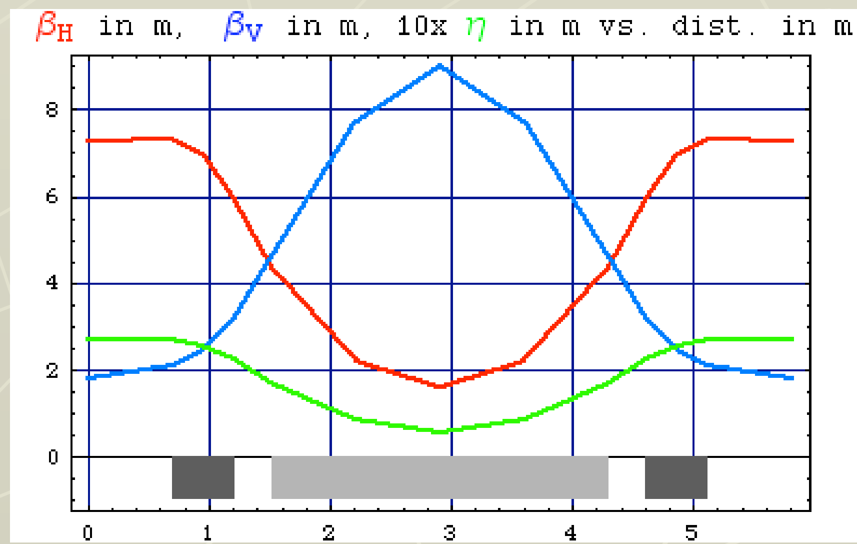
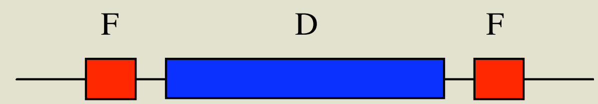


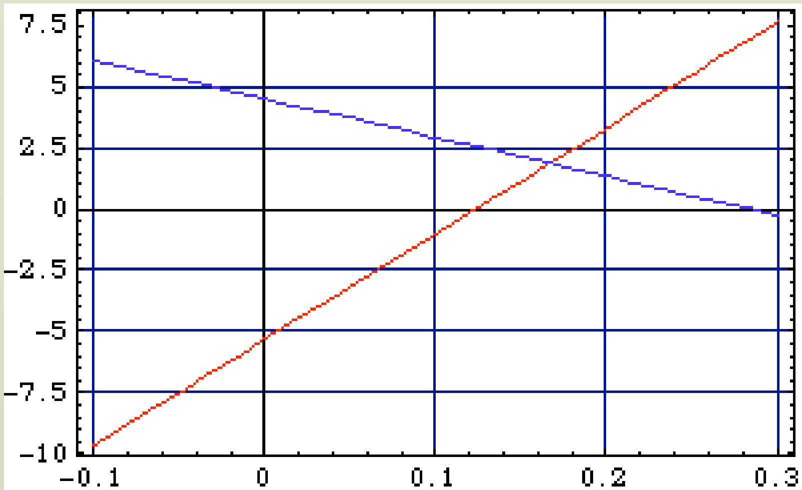
Table 2. Magnet Parameters

Magnet Type	F	D
Arc Length, m	0.509444	2.79514
Bending Field (B), kG	– 5.29169	4.51305
Gradient (G), kG/m	33.9174	–12.4036
Field Index, n = G/Bh	74.4451	–37.4293
Bend Radius (ρ = 1/h), m	–10.2943	12.0705
Bending Angle, mrad	–49.4877	231.569
Sagitta, cm	0.355537	9.12532

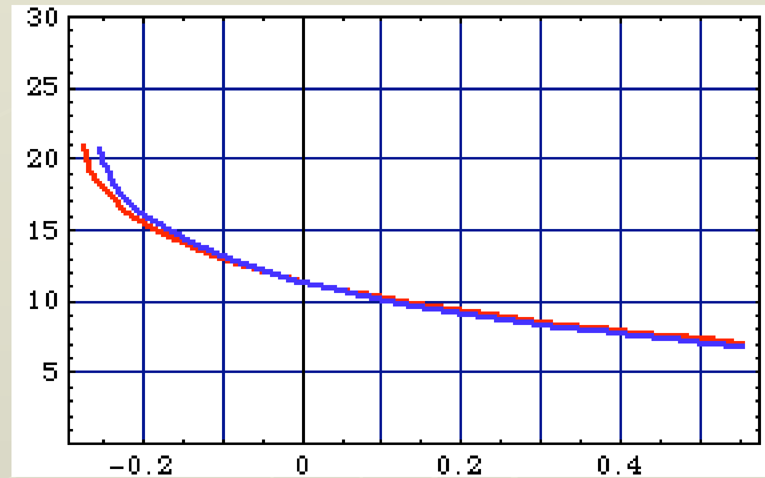
Linear Field Profile (1 of 2)



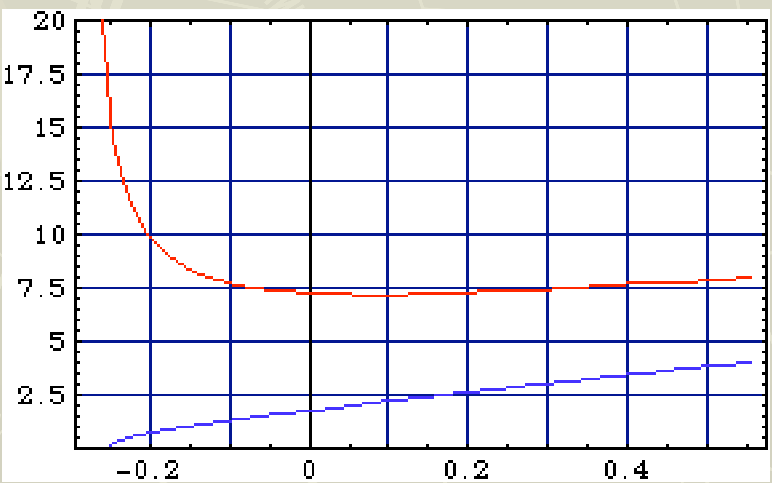
Field Profile (kG) vs. x (m) in
F-Sector Magnet (Red) D-Sector Magnet (Blue)



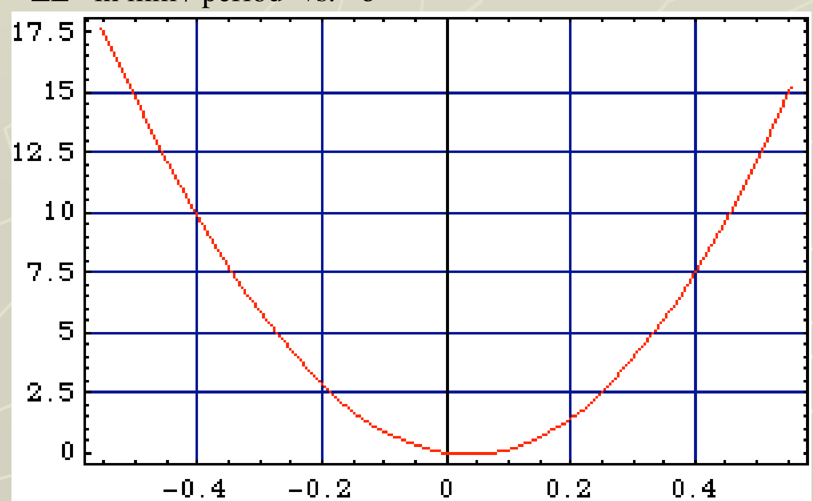
Tune variation vs. δ ν_H (Red) ν_V (Blue)



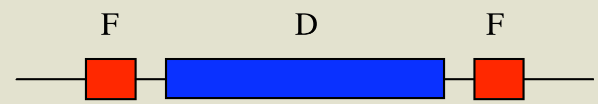
β_H (Red) and β_V (Blue) in m vs. δ
at the beginning of a period (S)



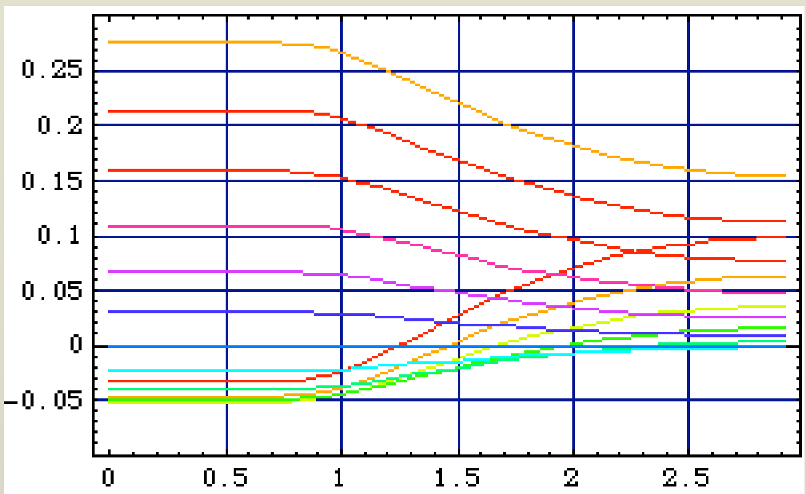
ΔL in mm / period vs. δ



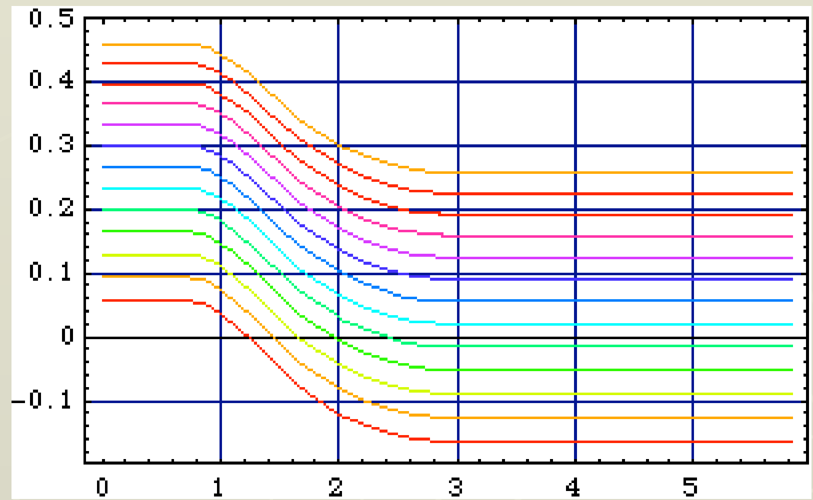
Linear Field Profile (2 of 2)



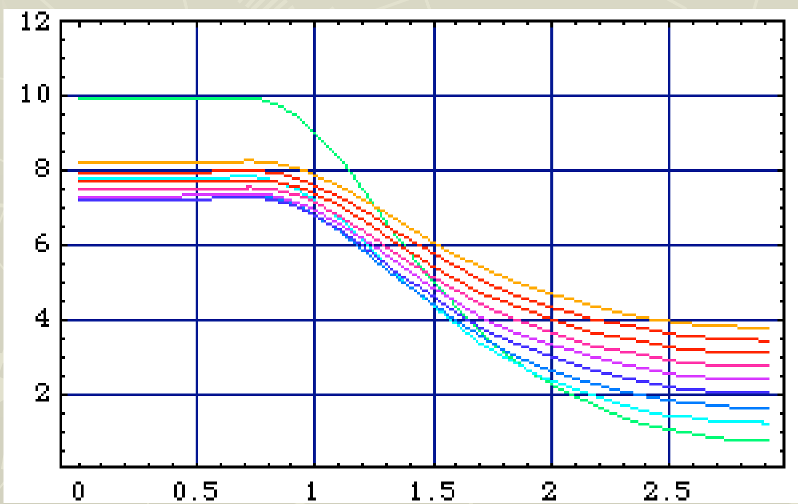
x_{co} (m) vs. period length (m) for $\delta = -0.6$ to $+0.6$ in steps of 0.1



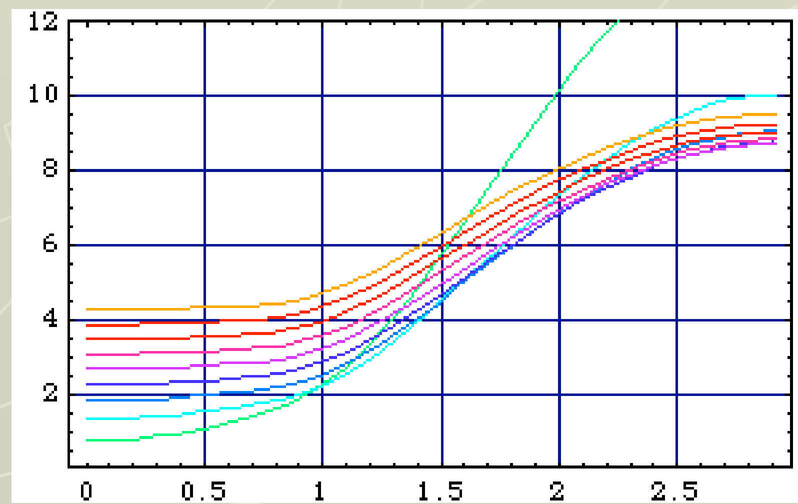
η (m) vs. period length (m) for $\delta = -0.6$ to $+0.6$ in steps of 0.1



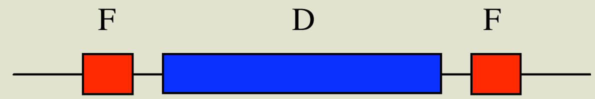
β_H (m) vs. period length (m) for $\delta = -0.6$ to $+0.6$ in steps of 0.1

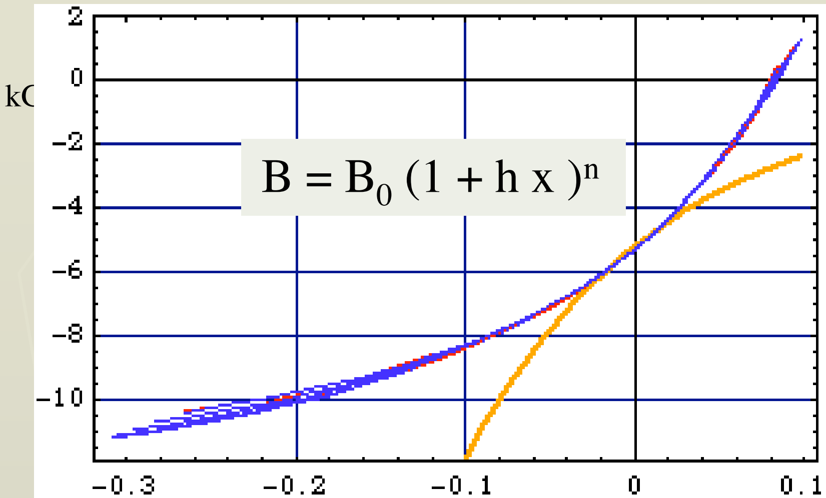


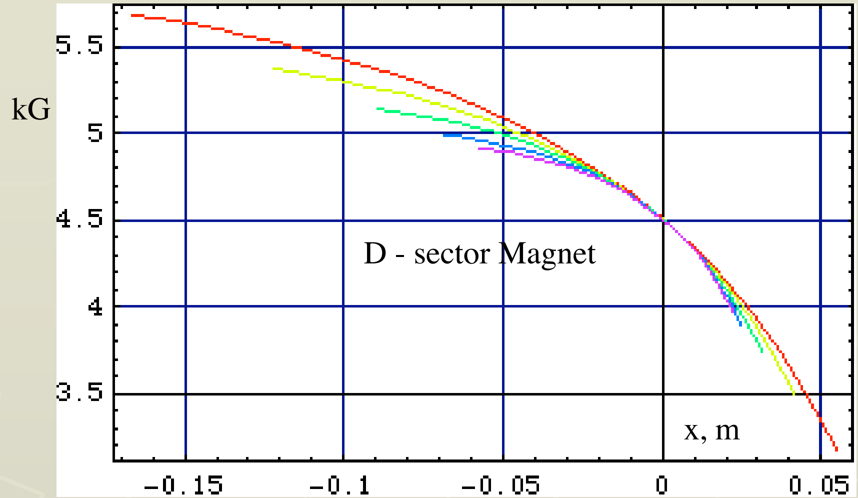
β_V (m) vs. period length (m) for $\delta = -0.6$ to $+0.6$ in steps of 0.1



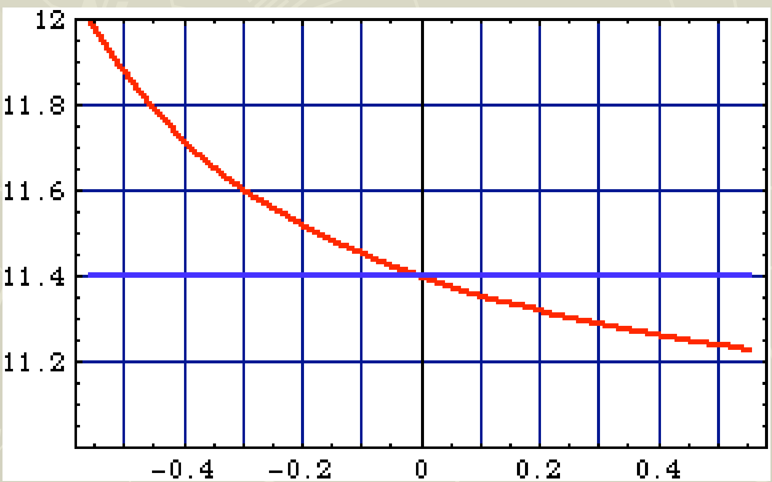
Adjusted Field Profile (1 of 2)



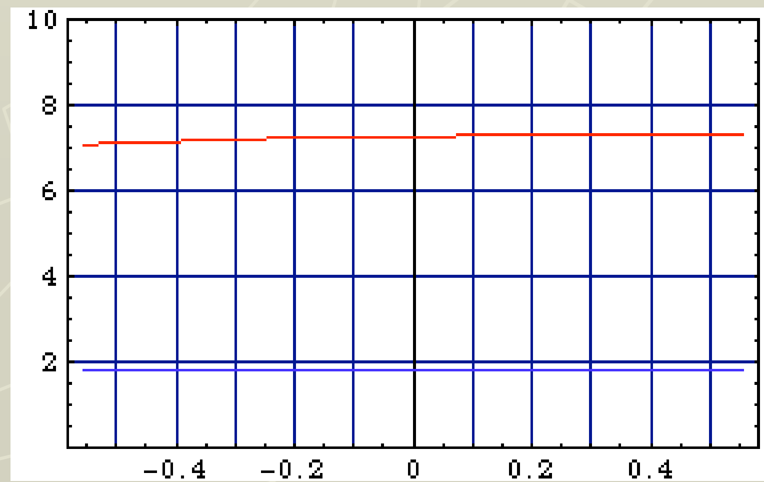




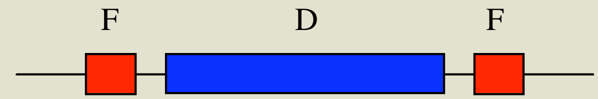
Tune variation vs. δ ν_H (Red) ν_V (Blue)

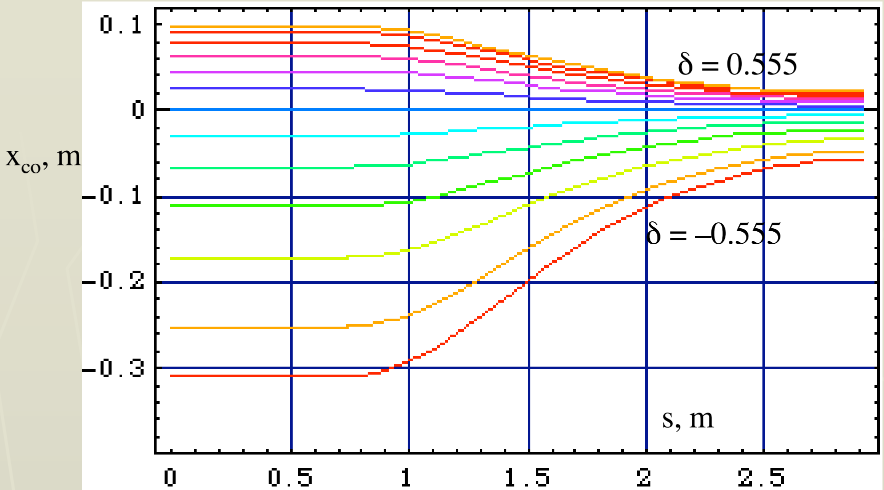


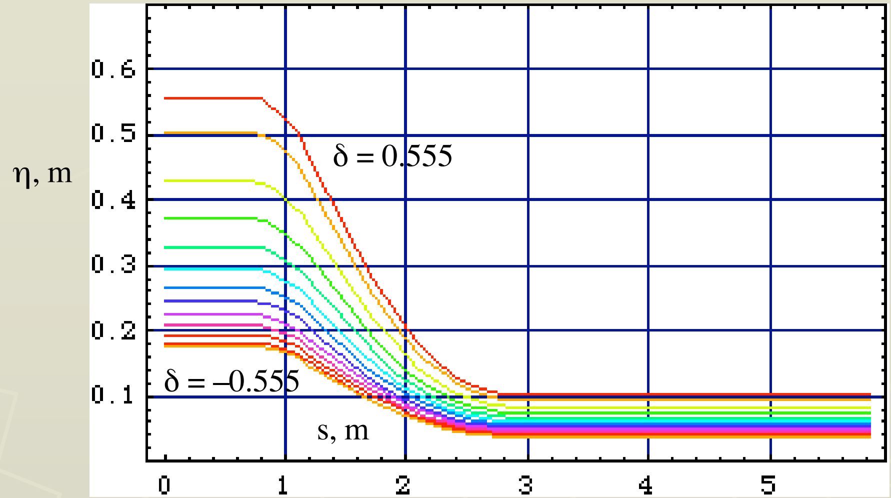
β_H (Red) and β_V (Blue) in m vs. δ
at the beginning of a period (S)

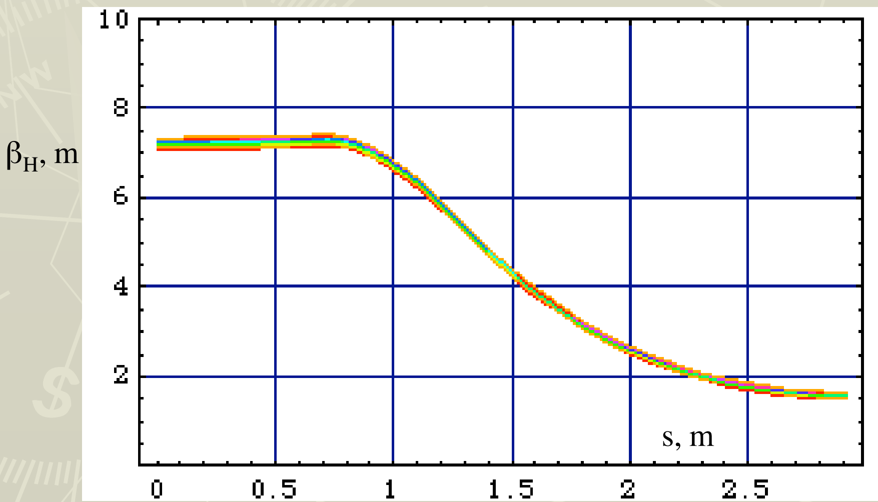


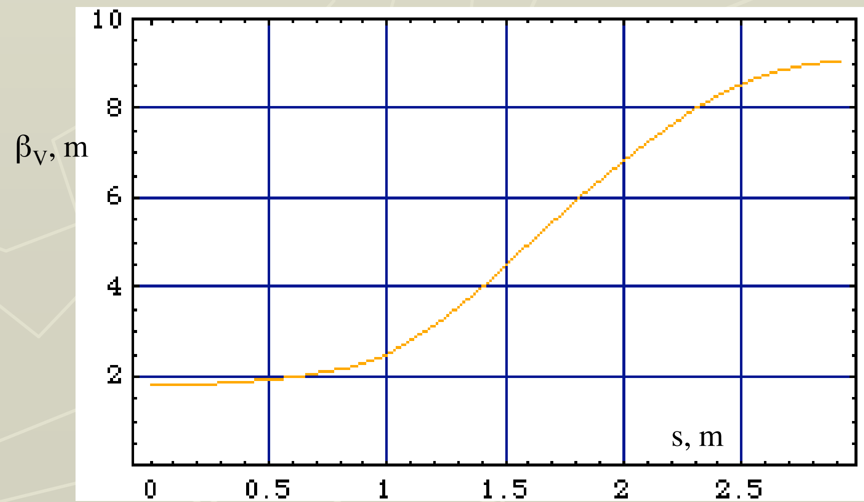
Adjusted Field Profile (2 of 2)



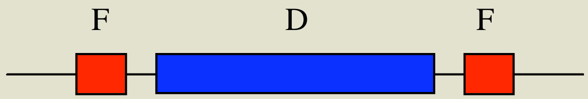








Sandro's Recipe (1 of 3)



C-A/AP/148

- Hamiltonian in Curvilinear Coordinate System (x, s, y)

$$H = -q A_s / c - (1 + h x) [p^2 - (p_x - q A_x / c)^2 - (p_y - q A_y / c)^2]^{1/2}$$

- (1) <u>Expand square root</u>

$$H = -q A_s / c - (1 + h x) p + (p_x - q A_x / c)^2 / 2 p + (p_y - q A_y / c)^2 / 2 p$$

- (2) <u>Drop higher order terms</u> like $hx(p_x - qA_x /c)^2$ and $hx(p_y - qA_y /c)^2$

- (3) <u>Assume that the magnetic field is given solely by the longitudinal component</u> A_s of the vector potential, whereas identically $A_x = A_y = 0$

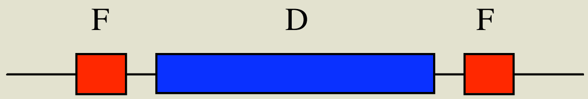
$$x'' = (q / pc)\, \partial A_s / \partial x + h$$ <-- Curvature Function $h = h(s)$

$$y'' = (q / pc)\, \partial A_s / \partial y$$

- Magnetic Field Components

$$(1 + hx)\, B_y = \partial A_s / \partial x$$
$$(1 + hx)\, B_x = -\partial A_s / \partial y$$

Sandro's Recipe (2 of 3)



- Equations of motion are now

$$x'' = (q / pc)\, B_y (1 + hx) + h$$

$$y'' = -\,(q / pc)\, B_x (1 + hx)$$

- Quite generally $\quad B(z) = B_0 + G(z)\, z$

$$B = B_y + i\, B_x \qquad\qquad z = x + i\, y$$

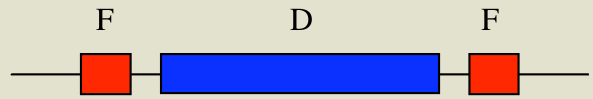
$$B_x = \text{Imaginary}\, \{B(z)\} \qquad \text{and} \qquad B_y = \text{Real}\, \{B(z)\}$$

- Motion on the y = 0 mid-plane

$$x'' = (q / pc)\, [B_0 + G(x)\, x]\, (1 + hx) + h$$

- Lorenz Condition $\quad (q\, B_0 / p_0 c) = -\, h \quad$ with $\quad p = p_0\, (1 + \delta)$

Sandro's Recipe (3 of 3)



- (4) <u>Neglect the higher order term</u> $(q / pc)\, G\, h\, x^2$
- Introduce the *field index* $n(x) = G(x) / h B_0$

$$x'' + h^2 (1 + n)\, x / (1 + \delta) = h\, \delta / (1 + \delta)$$
$$y'' - h^2\, n\, y / (1 + \delta) = 0$$

- Consider the general case where the field index is a nonlinear function of both x and s, namely $n = n(x, s)$. At any location s, for each momentum value δ there is one unique solution $x = x(\delta, s)$, and by *inversion* δ is a function of x and s, namely $\delta = \delta(x, s)$. We pose the following problem: Determine the field distribution, namely $n = n(x, s)$, that compensates the momentum dependence of $(1 + \delta)$ at the denominator:

$$n(x, s) = n_0 [1 + \delta(x, s)] \quad \text{-->} \quad G(x, s) = G_0 [1 + \delta(x, s)] \quad \text{<---}$$

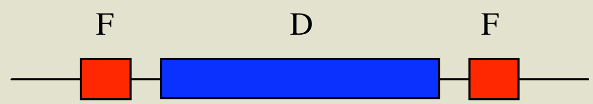
where n_0 is related to the gradient $G_0 = n_0\, h\, B_0$ on the reference trajectory.

- Then the equations of motion reduce to

$$x'' + h^2 x / (1 + \delta) + h^2 n_0 x = h\, \delta / (1 + \delta) \quad \text{-->} \quad x = x(\delta, s) \quad \text{-->} \quad \delta = \delta(x, s)$$
$$y'' - h^2 n_0\, y = 0$$

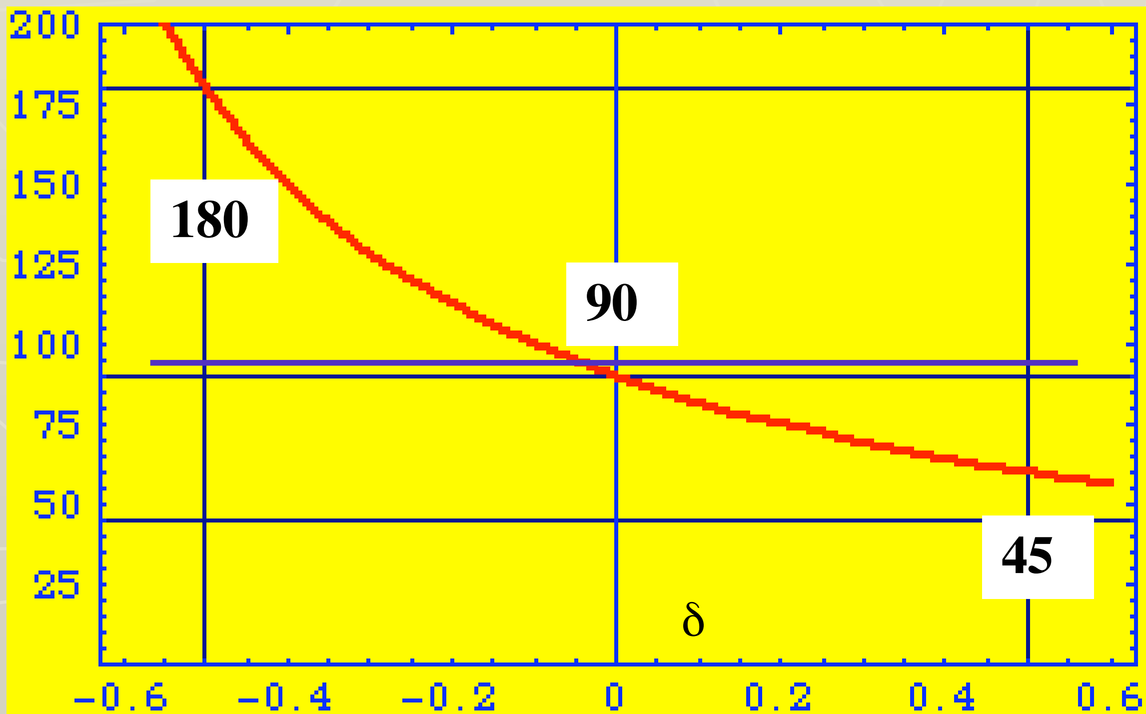
- WARNING: (5) A variation with s of the guiding field introduce a *solenoid component* that must be evaluated and taken into account in the particle dynamics.

Chromaticity with Linear Gradient

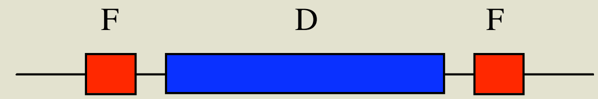


$$x'' + h^2 (1 + n)\, x / (1 + \delta) = h\, \delta / (1 + \delta)$$
$$y'' - h^2\, n\, y / (1 + \delta) = 0$$

$h^2\, n / (1 + \delta)$

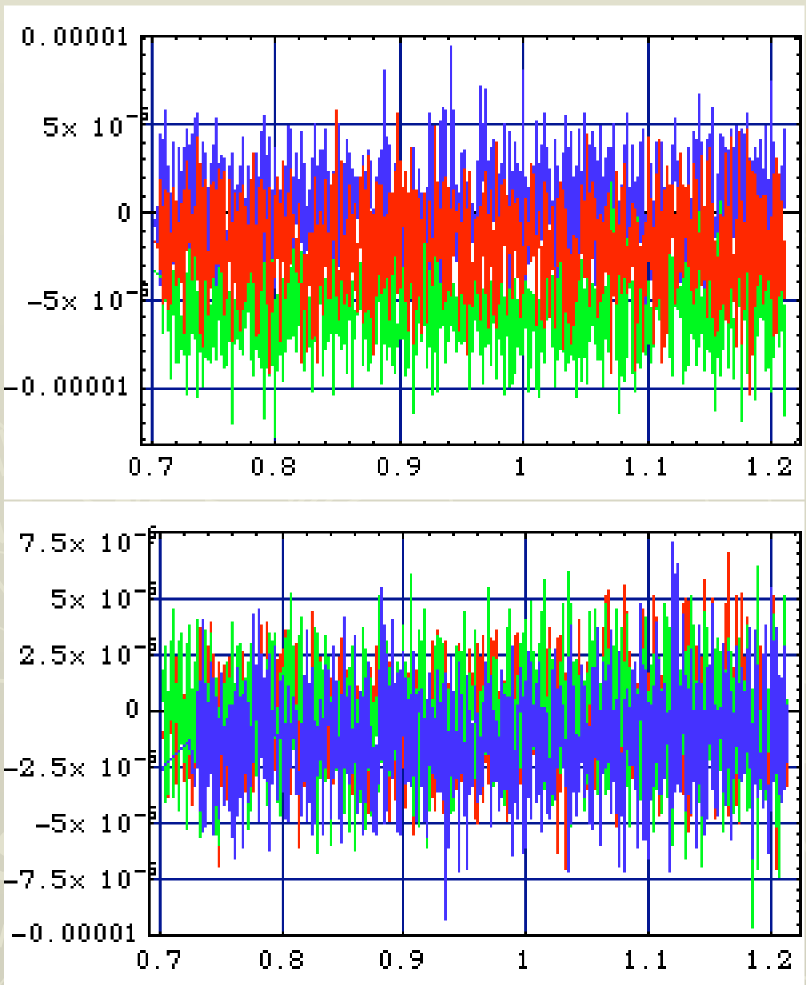


Proof of Sandro's Recipe (1 of 2)



By Direct Substitution of $x_{co}(\delta, s)$ in $x'' + h^2 [1 + n(x, s)]\, x / (1 + \delta) = h\,\delta / (1 + \delta)$

F - Sector



δ =

–0.55

–0.4

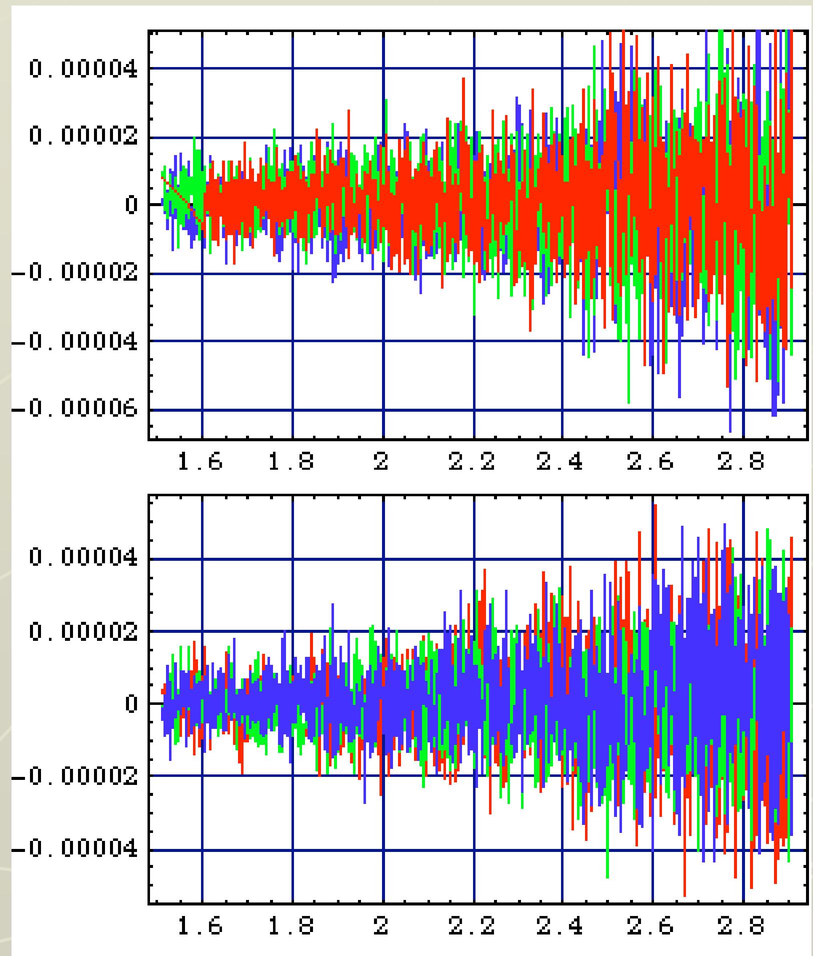
–0.2

0.2

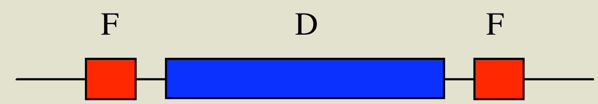
0.4

0.55

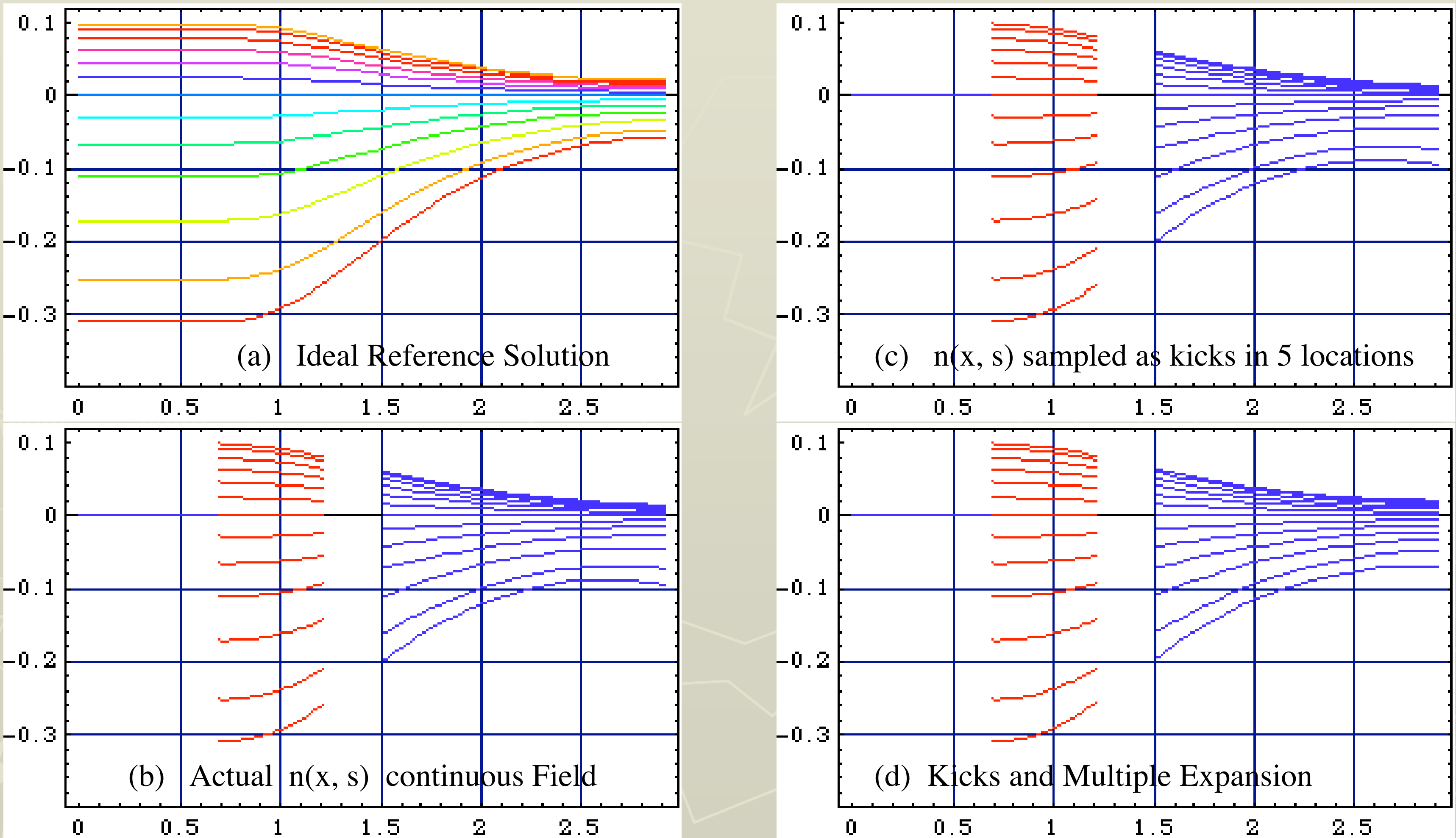
D - Sector



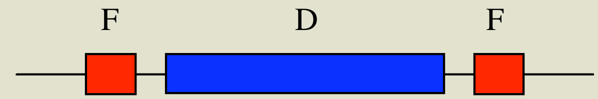
Proof of Sandro's Recipe (2 of 2)



By Direct Integration of $\quad x'' + h^2\,[1 + n(x, s)]\; x \,/\, (1 + \delta) \;=\; h\,\delta \,/\, (1 + \delta)$



Alternative Solutions



Other solutions are also possible. For instance, in order to flatten entirely the δ-dependence of the horizontal betatron tune, one can set the field profile so that

$$1 + n(x, s) = (1 + n_0)\,[1 + \delta(x, s)]$$

leading to the equations of motion

$$x'' + h^2 (1 + n_0)\, x = h\, \delta / (1 + \delta)$$
$$y'' - h^2 [\delta / (1 + \delta) + n_0]\, y = 0$$

There is now a (reduced) δ-dependence of the vertical betatron tune.
There is, of course, still dispersion on the horizontal plane.

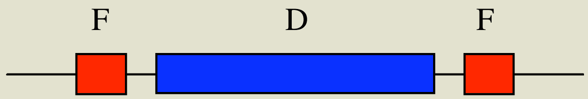
The field profile on the $y = 0$ mid-plane associated to this solution is given by

$$B(x, s) = B_0 + G_0\, [1 + \delta(x, s)\, (1 + 1/n_0)]$$

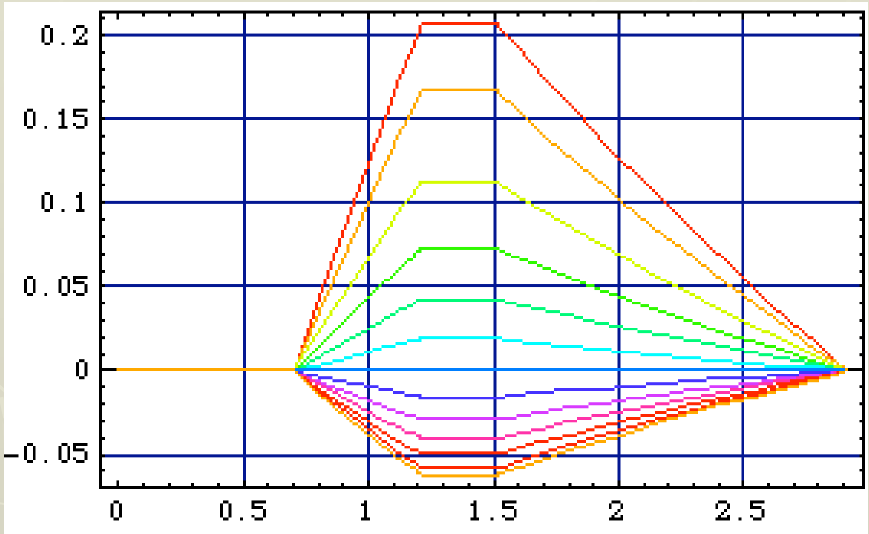
that, as long $n_0 >> 1$, is only slightly different from the previously derived field profile.

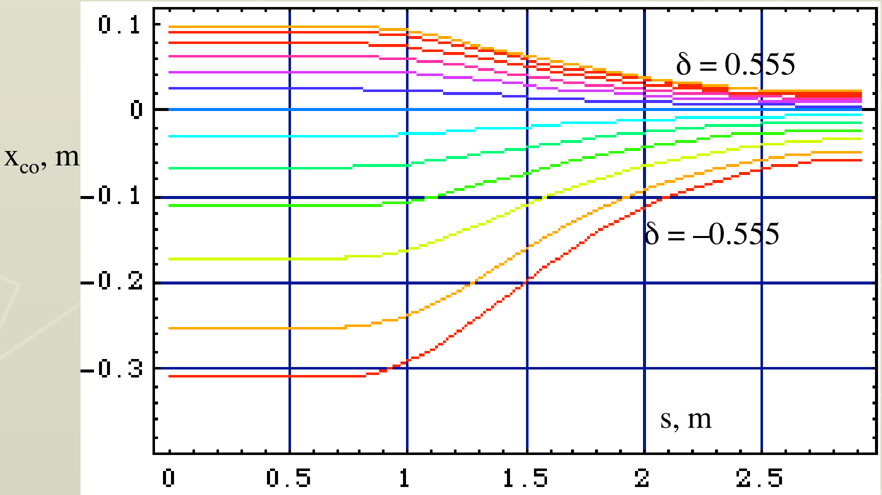
If desired, always in the search for an optimum cancellation of the chromatic and dispersive behavior, intermediate solutions can be found.

Edge Effect (1 of 2)



x_{co}' in rad versus path length s in meter, for $\delta = \pm 0.555$

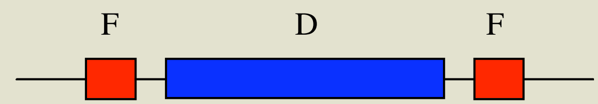




MATHEMATICA

Presentation to C-A Department June 4, 2004

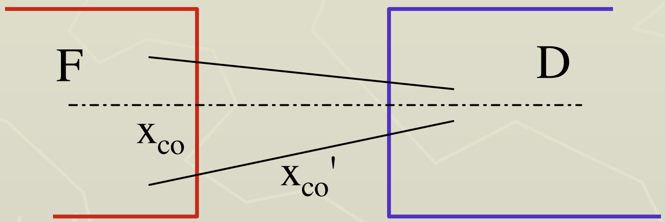
Edge Effect (2 of 2)

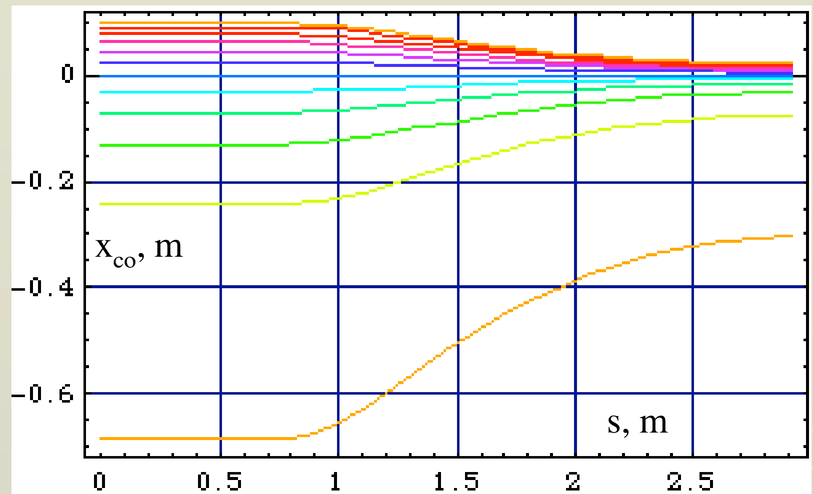


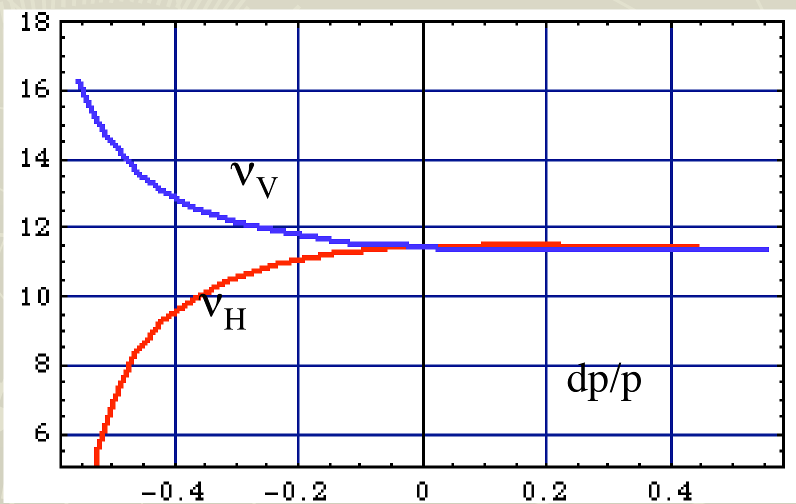
$$\Delta y' = -\frac{h_i\, B_i(x_{co})}{B_i\,(1+\delta)}\,(\tan x_{co}')\, y$$

Vertical == Focusing

Horizontal == Defocusing

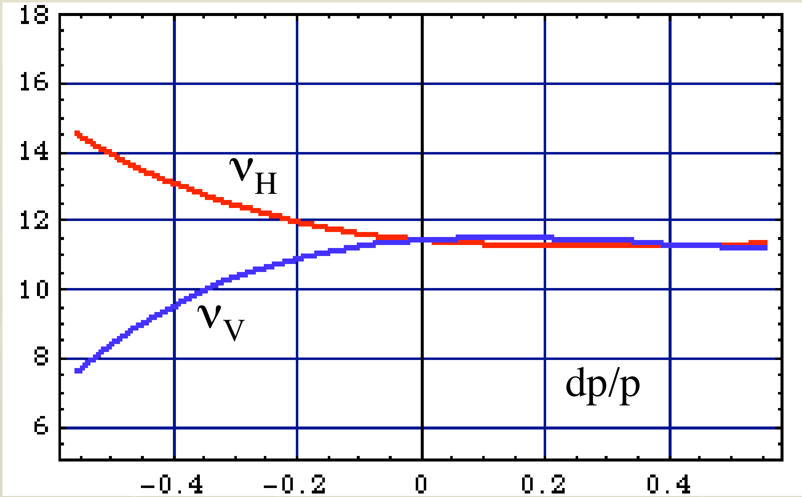


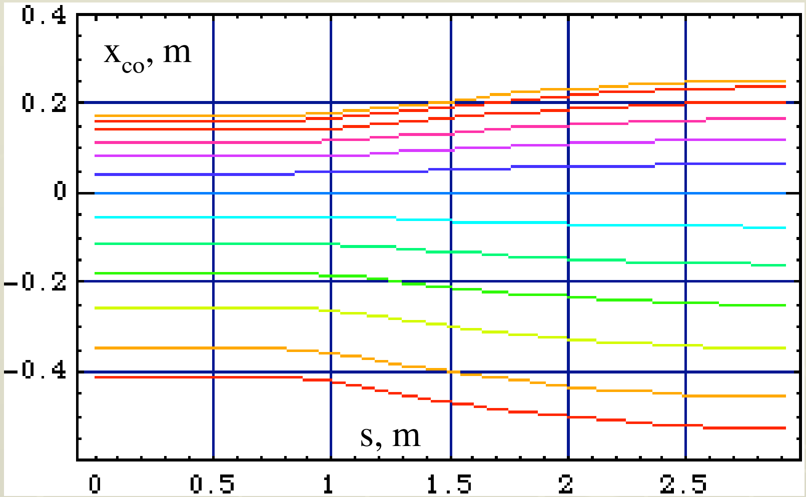


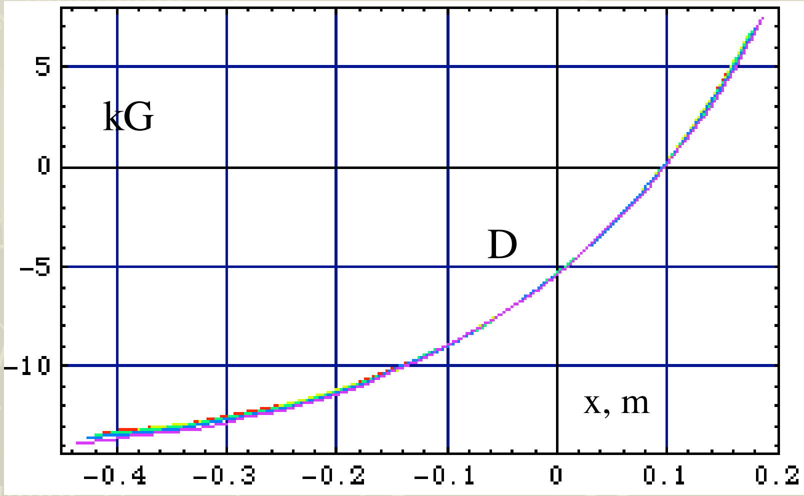


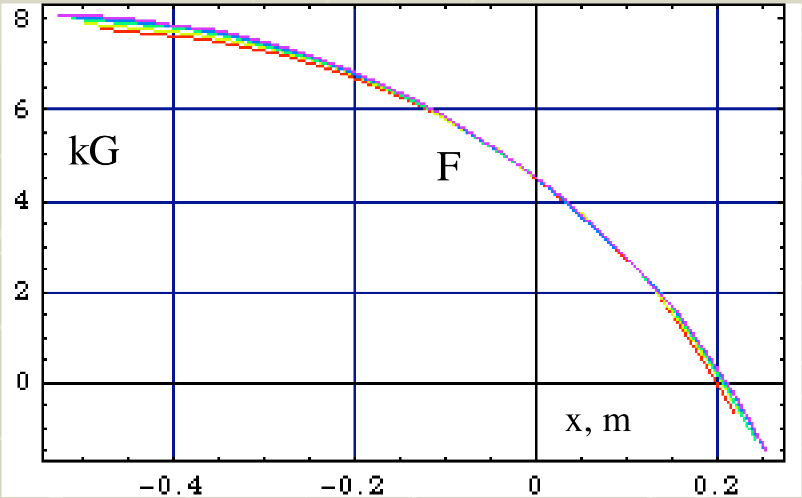
- Edge Effect is important and it cannot be neglected. In the case of the FDF-triplet arrangement there is a problem for large negative values of δ.
- If we accept the *recipe* for the **Adjusted Field Profile**, we could also apply it to the DFD-triplet arrangement. Maybe in this case the problem will shift to large positive values of δ (let us check!…)
- I am aware that the DFD-triplet is desirable for the accommodation of injection/extraction components and RF cavities, but it could make the central magnet wider.

DFD - Triplet

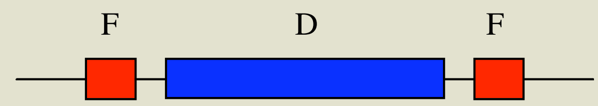


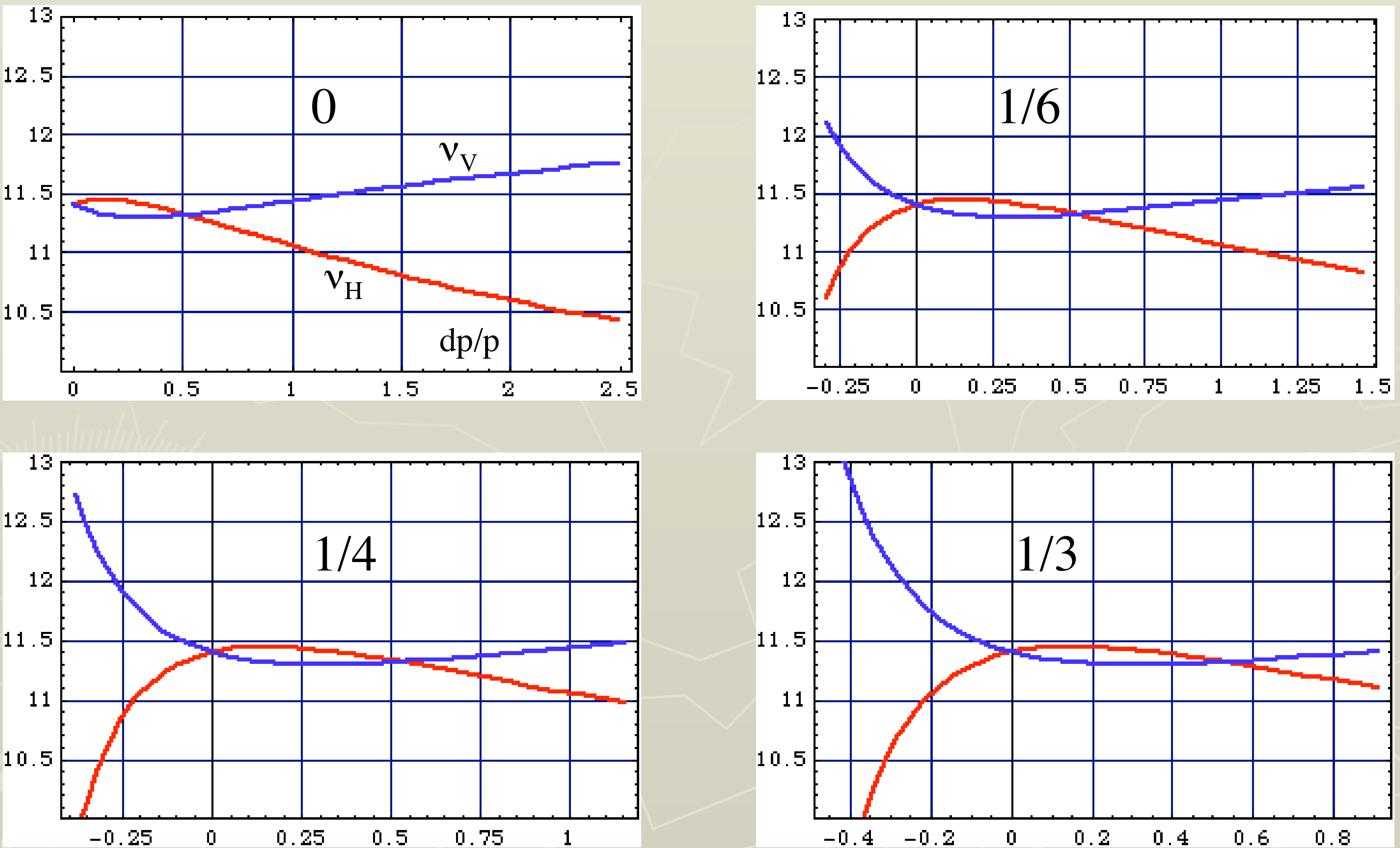




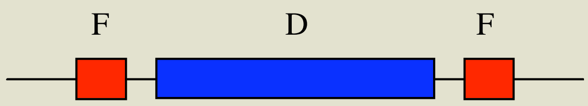


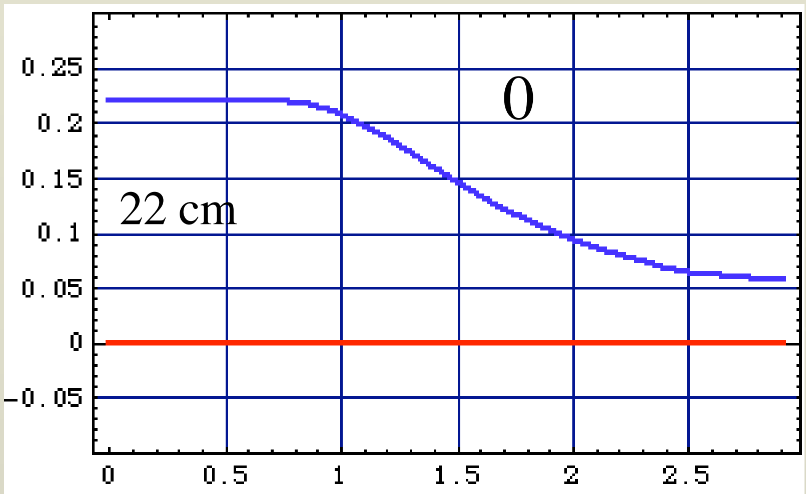
Reference Trajectory (1 of 2)

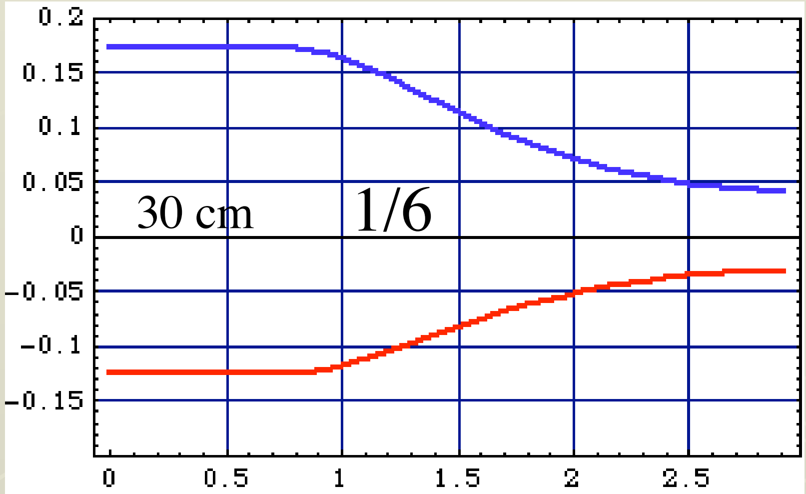


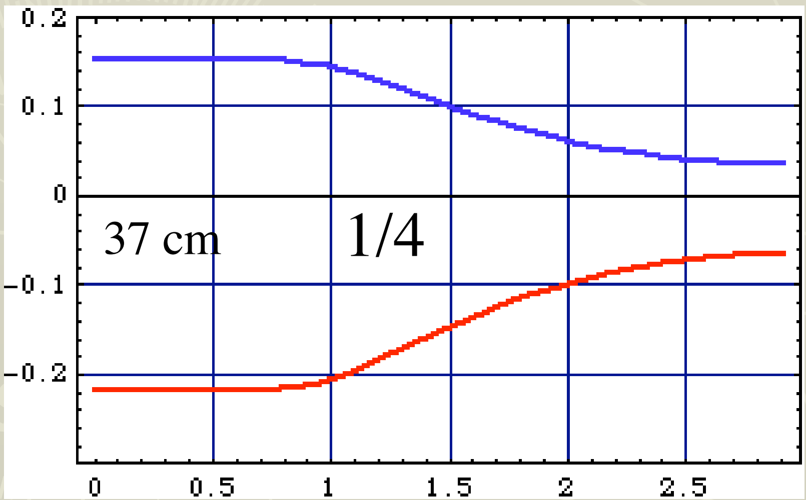


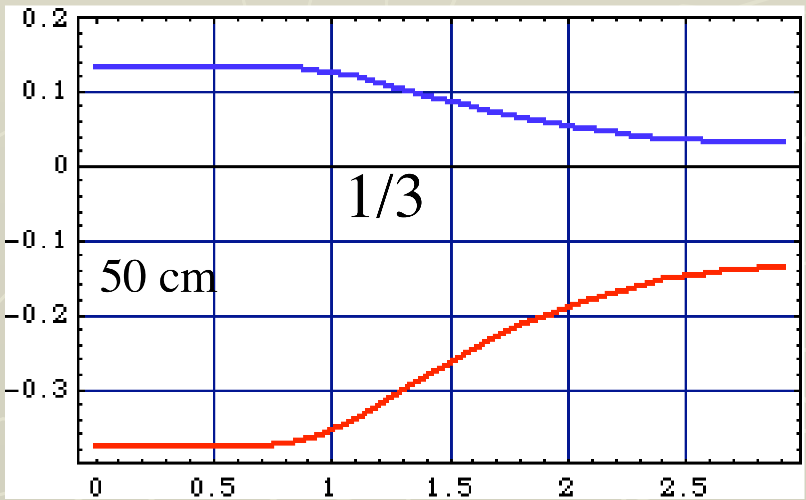
Reference Trajectory (2 of 2)



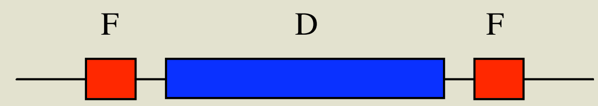


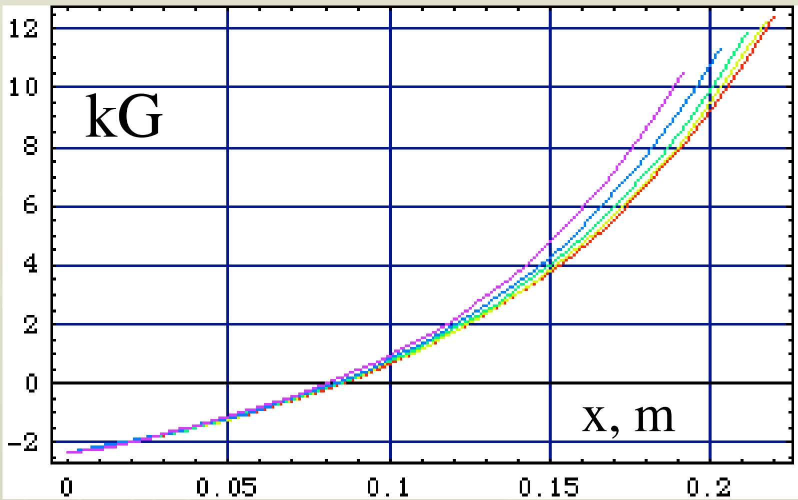






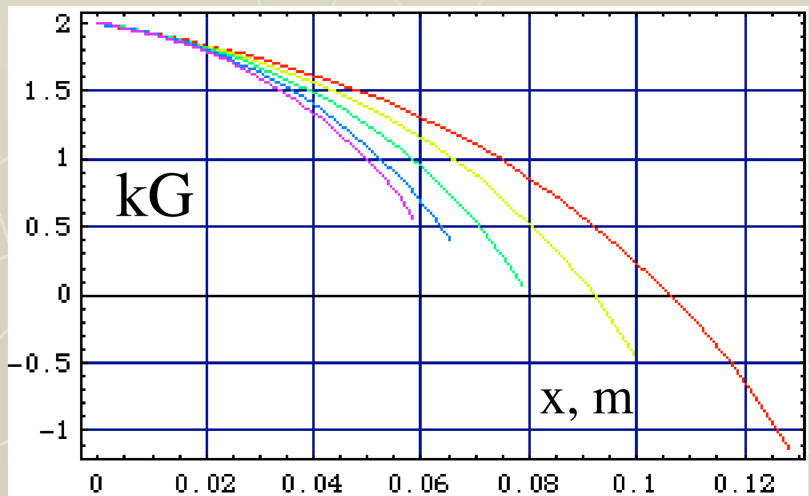
Field Profile for ref traj at δ = 0



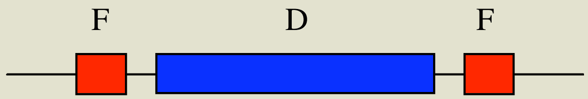


<-- F - Magnet

D - Magnet -->



Two instead of One

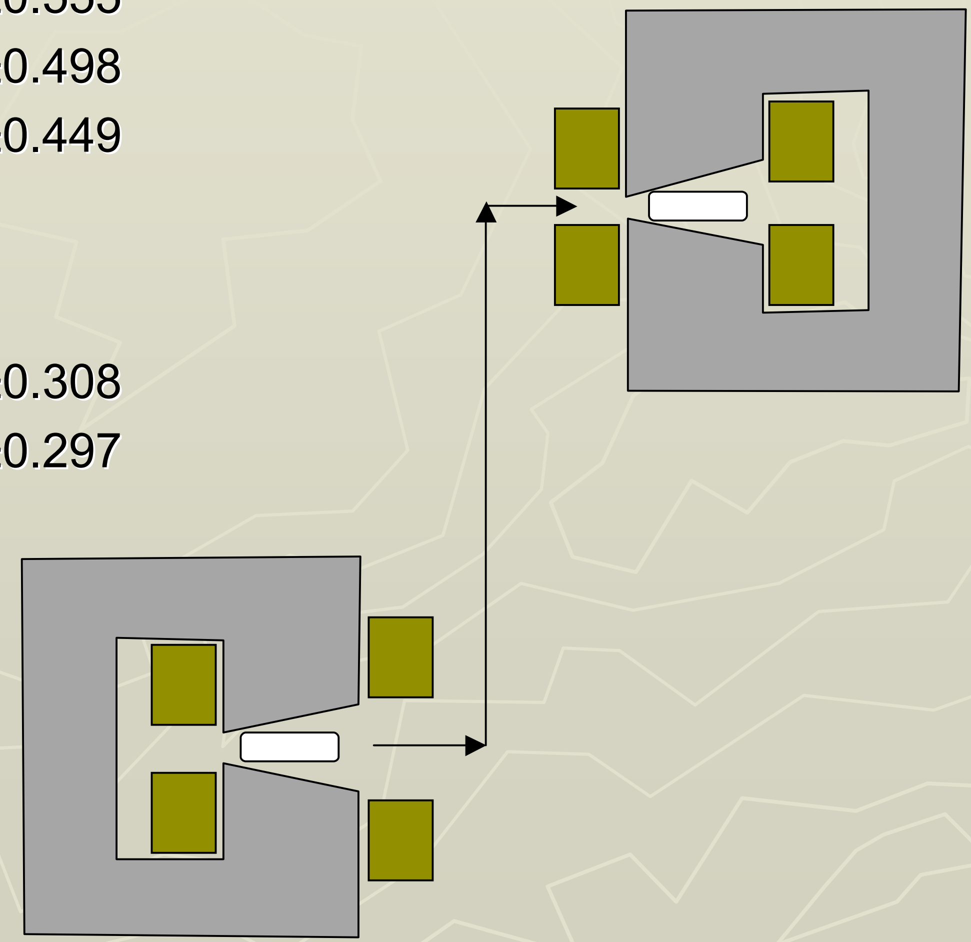


Single Ring:

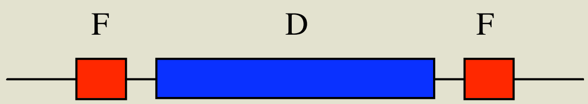
	$\Delta p/p$
200 MeV - 1,500 MeV	±0.555
200 MeV - 1,200 MeV	±0.498
200 MeV - 1,000 MeV	±0.449

Double Rings:

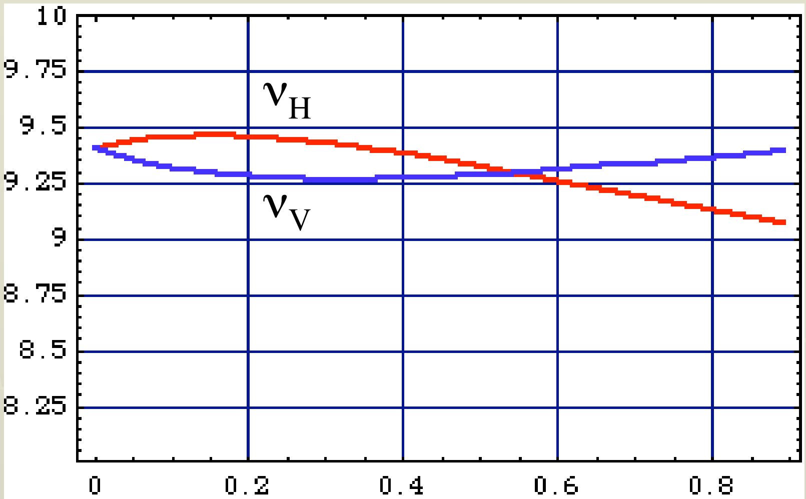
200 MeV - 600 MeV	±0.308
600 MeV - 1,500 MeV	±0.297

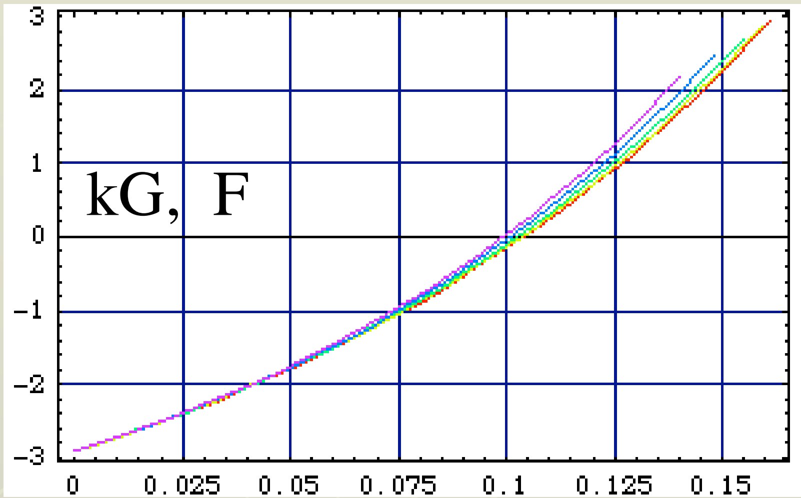


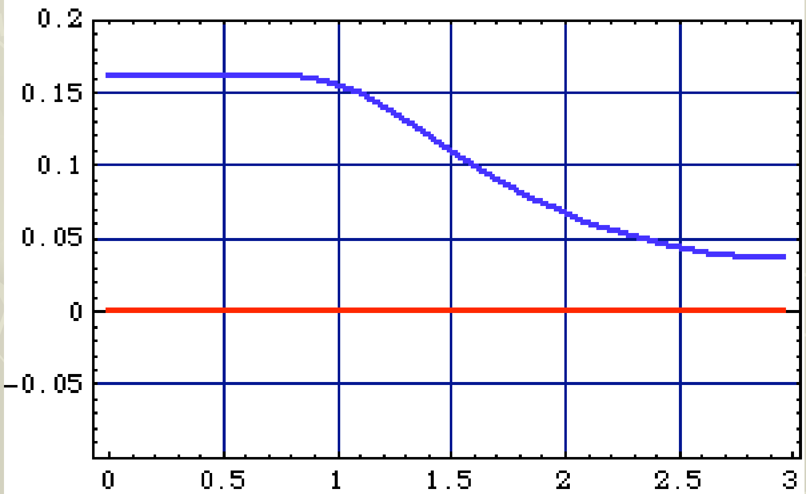
1st FFAG 200 - 600 MeV

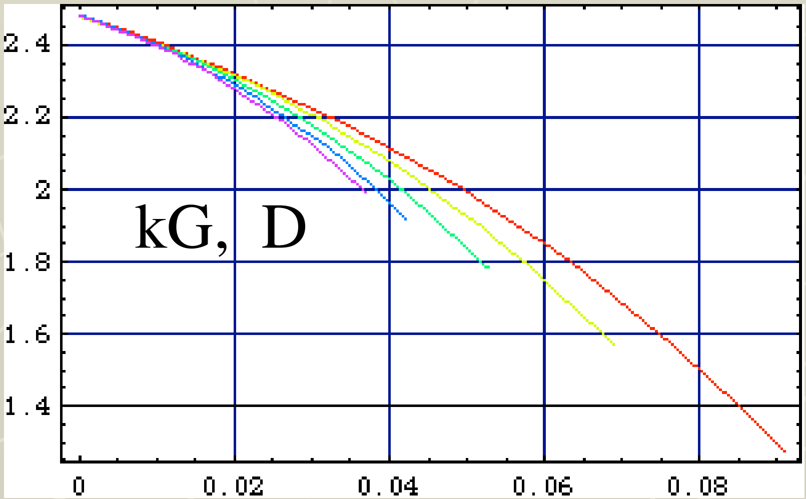


$N_p = 33$ $C = 195.36$ m

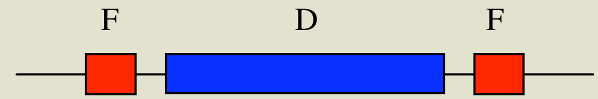




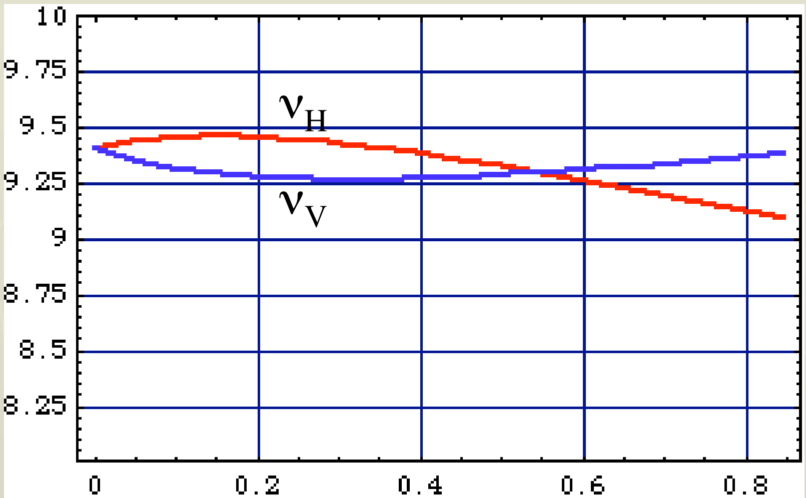


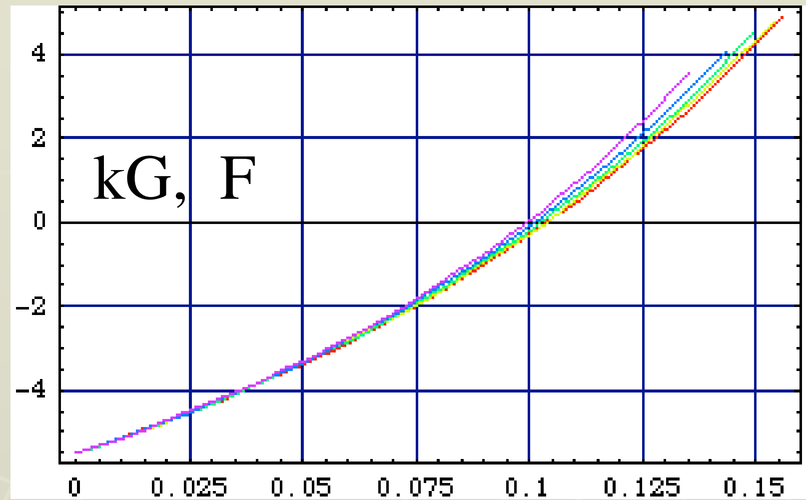


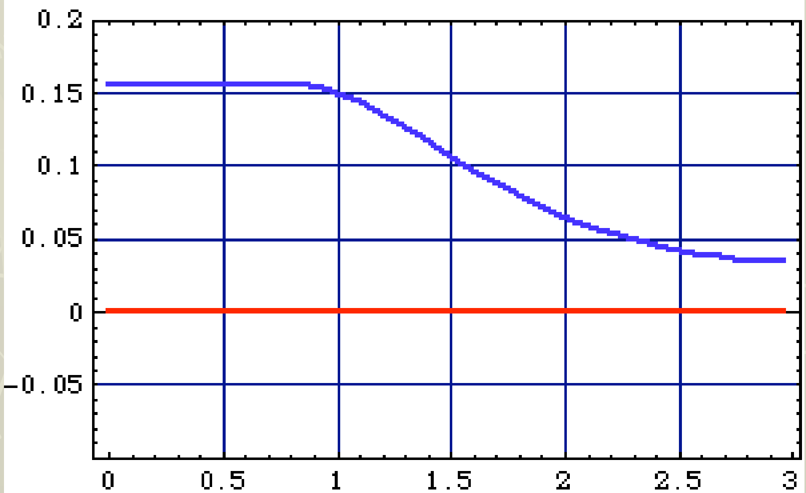
2nd FFAG 600 - 1,500 MeV

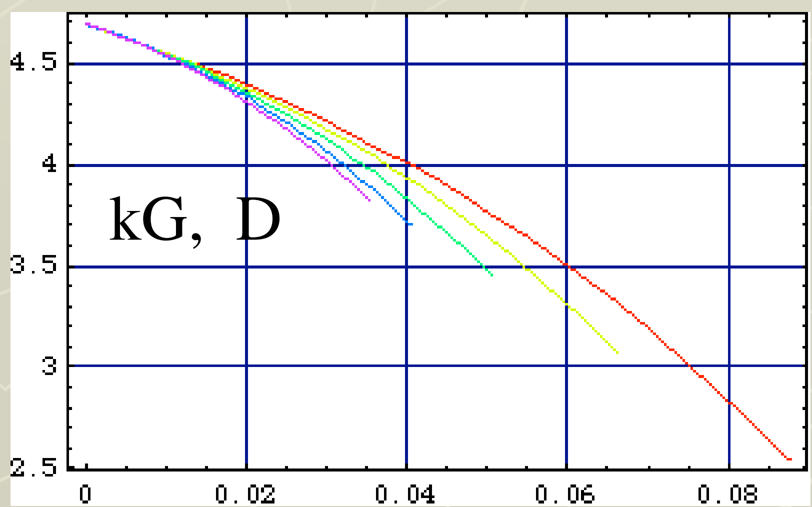


$N_p = 34$ $\qquad$ $C = 201.28$ m

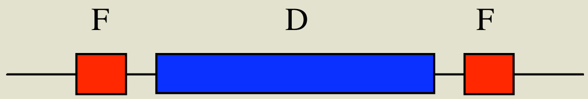


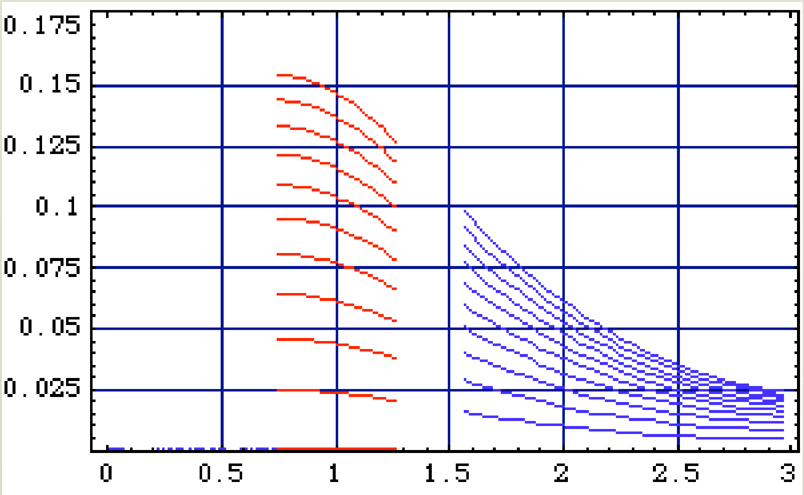


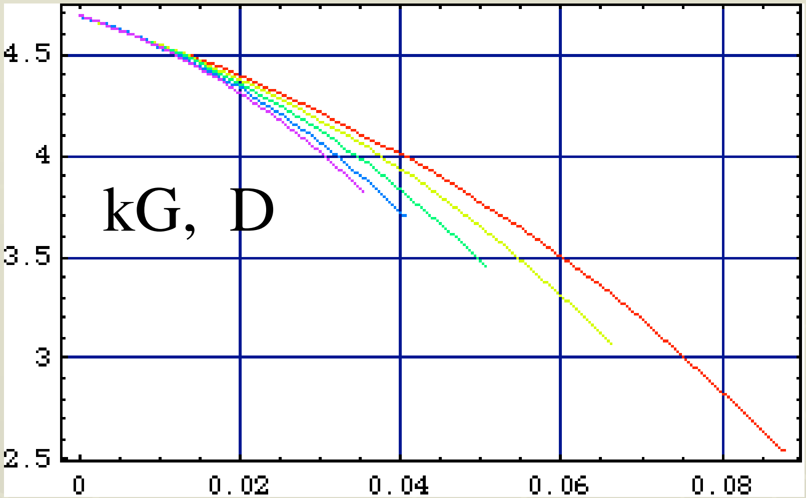


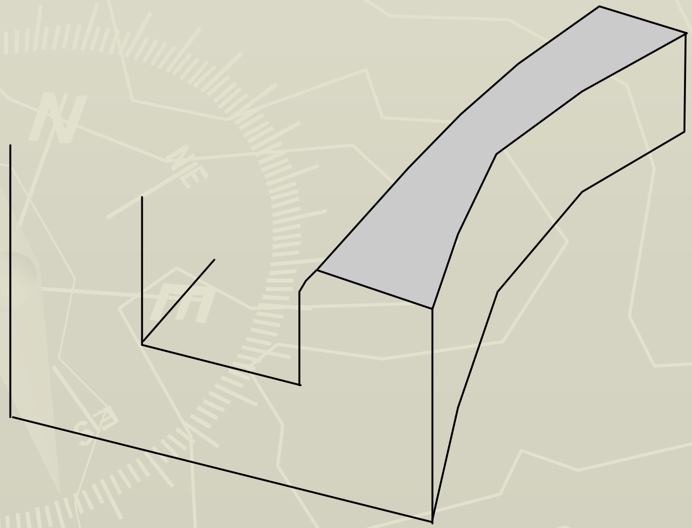


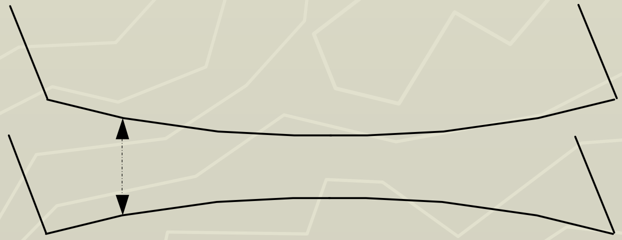
Magnet Design





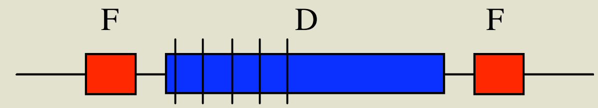






Minimum Gap	10 cm
Maximum Width	15 cm

Multiple Expansion




```
tablen1 = Table[{x, ffB21[x]}, {x, tblsc2[0, 1], tblsc2[1, 1], 1/100}];
f21 = FindFit[tablen1, B2 - G2 x + 50 (a12 x x /2! + a13 x x x /3! + a14 x x x x /4! + a15 x x x x x /5!)/L2, {a12, a13, a14, a15}, x]
fldB21[x_] := B2 - G2 x + 50 (a12 x x/2! + a13 x x x/3! + a14 x x x x/4! + a15 x x x x x/5!)/L2 /. f21;

tablen2 = Table[{x, ffB22[x]}, {x, tblsc2[0, 2], tblsc2[1, 2], 1/100}];
f22 = FindFit[tablen2, B2 - G2 x + 50 (a22 x x /2! + a23 x x x /3! + a24 x x x x /4! + a25 x x x x x /5!)/L2, {a22, a23, a24, a25}, x]
fldB22[x_] := B2 - G2 x + 50 (a22 x x/2! + a23 x x x /3! + a24 x x x x /4! + a25 x x x x x/5!)/L2 /. f22;

tablen3 = Table[{x, ffB23[x]}, {x, tblsc2[0, 3], tblsc2[1, 3], 1/100}];
f23 = FindFit[tablen3, B2 - G2 x + 50 (a32 x x /2! + a33 x x x /3! + a34 x x x x /4! + a35 x x x x x /5!)/L2, {a32, a33, a34, a35}, x]
fldB23[x_] := B2 - G2 x + 50 (a32 x x /2! + a33 x x x /3! + a34 x x x x /4! + a35 x x x x x/5!)/L2 /. f23;

tablen4 = Table[{x, ffB24[x]}, {x, tblsc2[0, 4], tblsc2[1, 4], 1/100}];
f24 = FindFit[tablen4, B2 - G2 x + 50 (a42 x x /2! + a43 x x x /3! + a44 x x x x /4! + a45 x x x x x /5!)/L2, {a42, a43, a44, a45}, x]
fldB24[x_] := B2 - G2 x + 50 (a42 x x/2! + a43 x x x /3! + a44 x x x x /4! + a45 x x x x x/5!)/L2 /. f24;

tablen5 = Table[{x, ffB25[x]}, {x, tblsc2[0, 5], tblsc2[1, 5], 1/100}];
f25 = FindFit[tablen5, B2 - G2 x + 50 (a52 x x /2! + a53 x x x /3! + a54 x x x x /4! + a55 x x x x x /5!)/L2, {a52, a53, a54, a55}, x]
fldB25[x_] := B2 - G2 x + 50 (a52 x x/2! + a53 x x x /3! + a54 x x x x /4! + a55 x x x x x/5!)/L2 /. f25;

{a12 → -4.232655311713346, a13 → -89.59973089484862, a14 → -953.1506613580015, a15 → 6791.009144574469}

{a22 → -5.685262451055018, a23 → -175.6891898844062, a24 → -1223.845907095543, a25 → 40861.41277040269}

{a32 → -7.621158731065018, a33 → -333.0805211091171, a34 → -996.6210049149577, a35 → 269605.4705855781}

{a42 → -9.956071799401875, a43 → -494.4575260830500, a44 → -16977.38138153995, a45 → 2.750155386705654 × 10^6}

{a52 → -11.74124249008848, a53 → -654.2919120120293, a54 → -22141.28562687770, a55 → 4.591141269769532 × 10^6}

bplt21 = Plot[{ffB21[x], fldB21[x]}, {x, tblsc2[0, 1], tblsc2[1, 1]},
   PlotStyle → {{Hue[0.0], Thickness[0.007]}, {Hue[0.7], Thickness[0.007]}}, Frame → True, Imag
bplt22 = Plot[{ffB22[x], fldB22[x]}, {x, tblsc2[0, 2], tblsc2[1, 2]},
   PlotStyle → {{Hue[0.0], Thickness[0.007]}, {Hue[0.7], Thickness[0.007]}}, Frame → True, Imag
bplt23 = Plot[{ffB23[x], fldB23[x]}, {x, tblsc2[0, 3], tblsc2[1, 3]},
   PlotStyle → {{Hue[0.0], Thickness[0.007]}, {Hue[0.7], Thickness[0.007]}}, Frame → True, Imag
bplt24 = Plot[{ffB24[x], fldB24[x]}, {x, tblsc2[0, 4], tblsc2[1, 4]},
   PlotStyle → {{Hue[0.0], Thickness[0.007]}, {Hue[0.7], Thickness[0.007]}}, Frame → True, Imag
bplt25 = Plot[{ffB25[x], fldB25[x]}, {x, tblsc2[0, 5], tblsc2[1, 5]},
   PlotStyle → {{Hue[0.0], Thickness[0.007]}, {Hue[0.7], Thickness[0.007]}}, Frame → True, Imag
Show[bplt21, bplt22, bplt23, bplt24, bplt25, Frame → True, ImageSize → 300, GridLines → Automat
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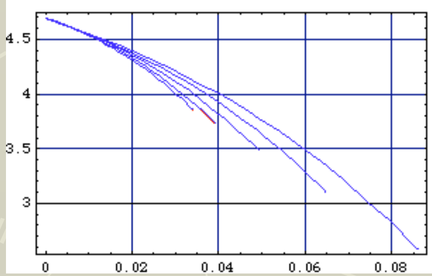
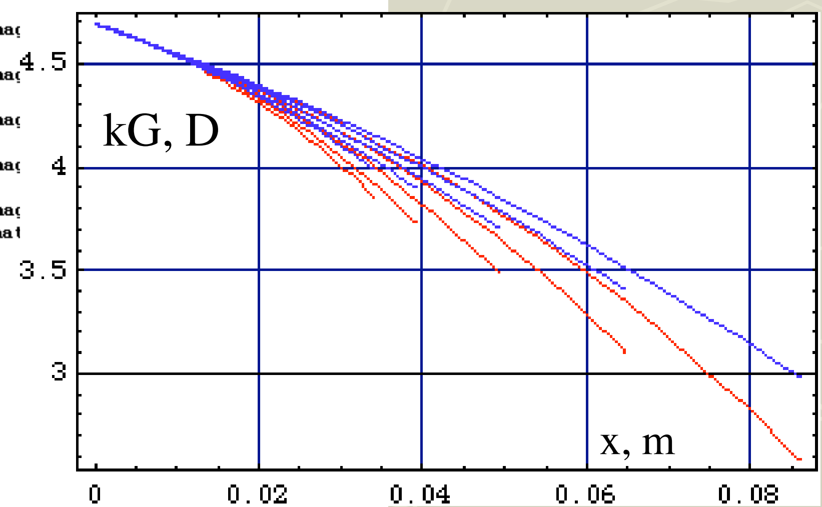
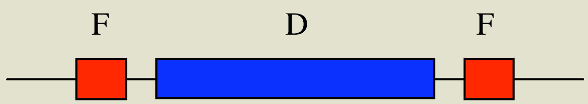


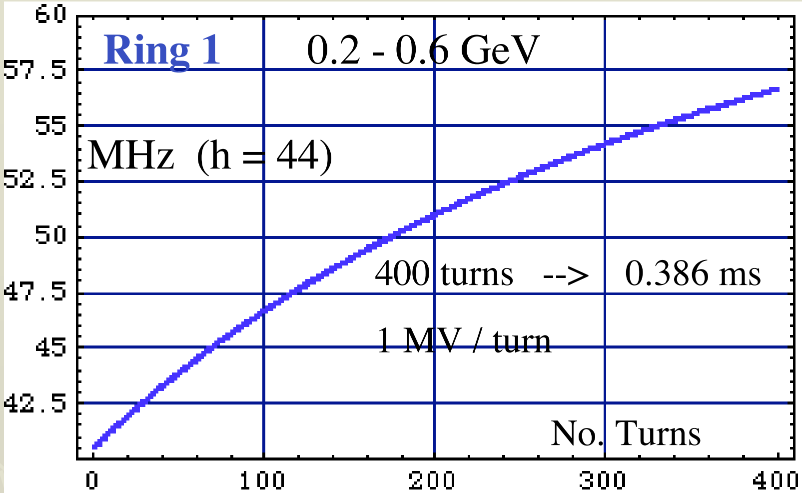


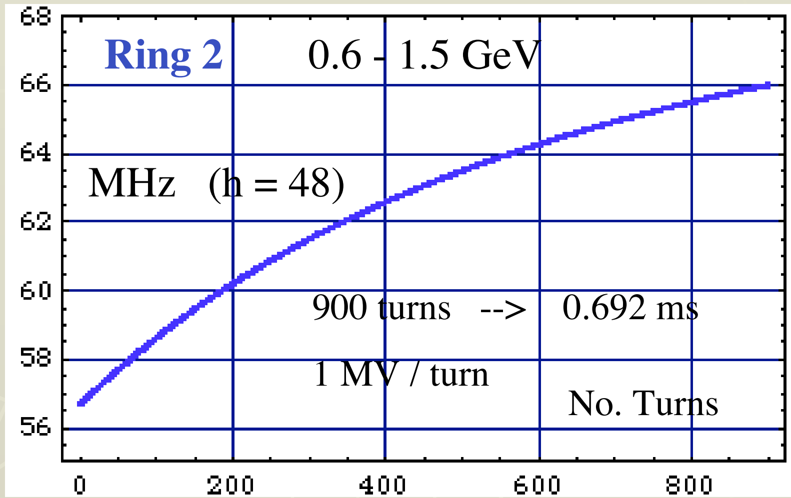
Acceleration:
Frequency Modulation

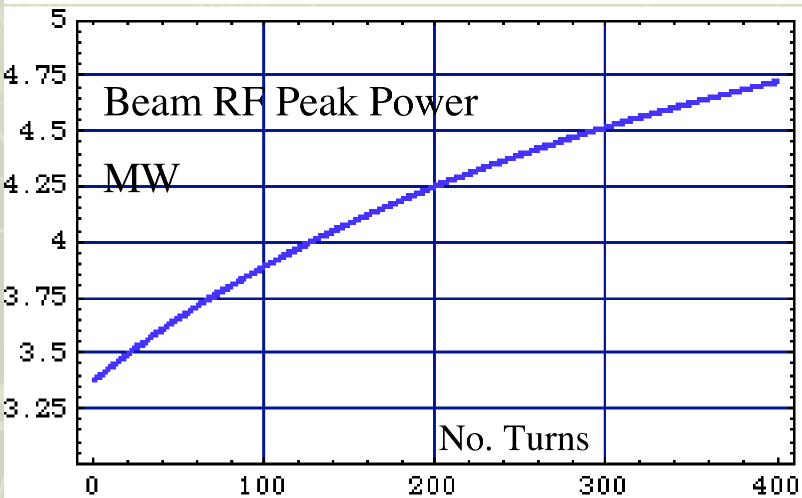


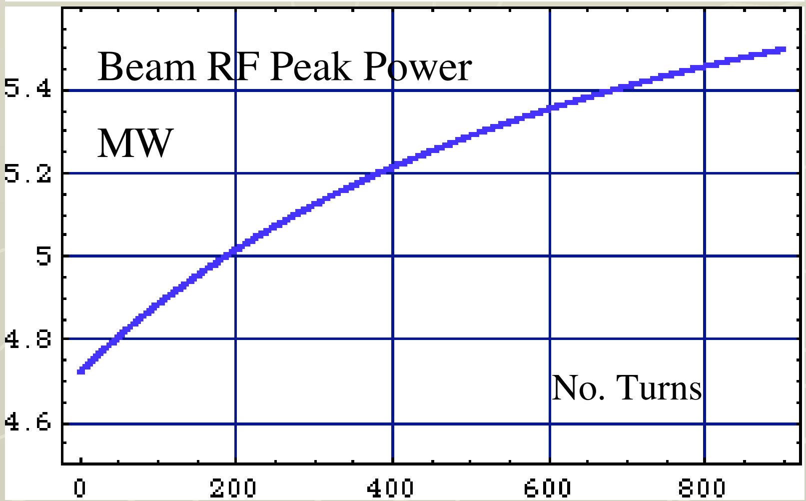
No. of Protons / pulse 2.5×10^{13}
RF @ Inj / 201.25 MHz   1/6

Single-Gap Cavity: 1.2 m long   50-100 kV
W: 20 cm   H: 10 cm

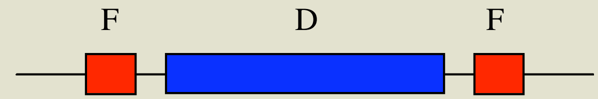








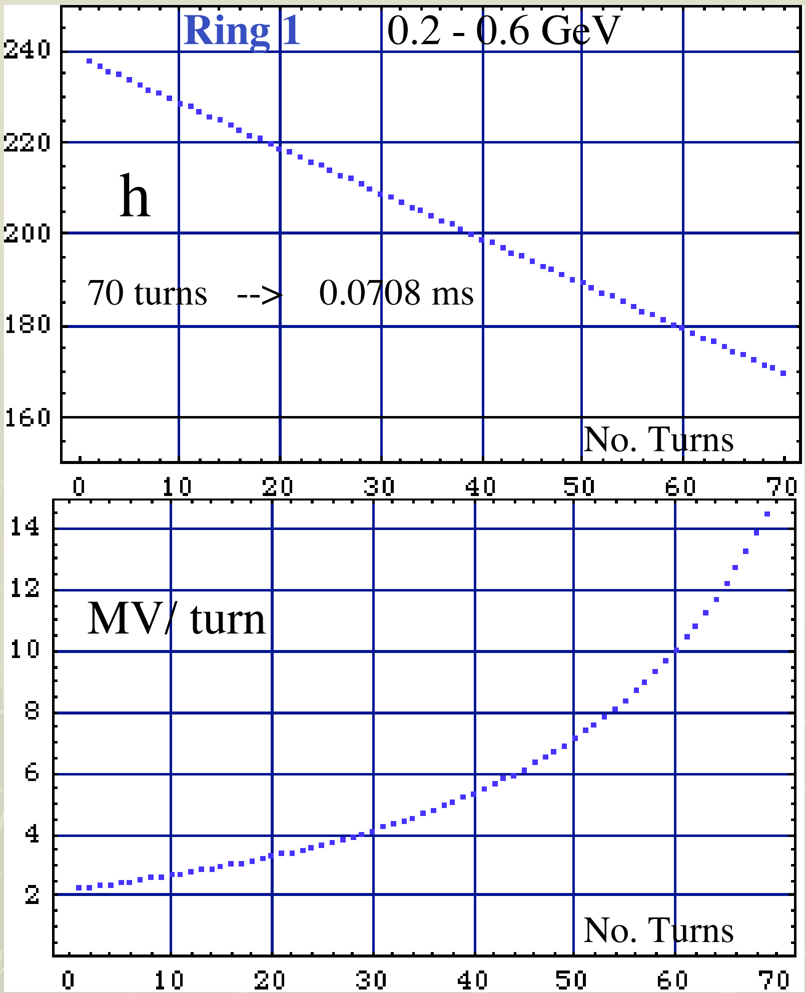
Acceleration: Voltage Modulation

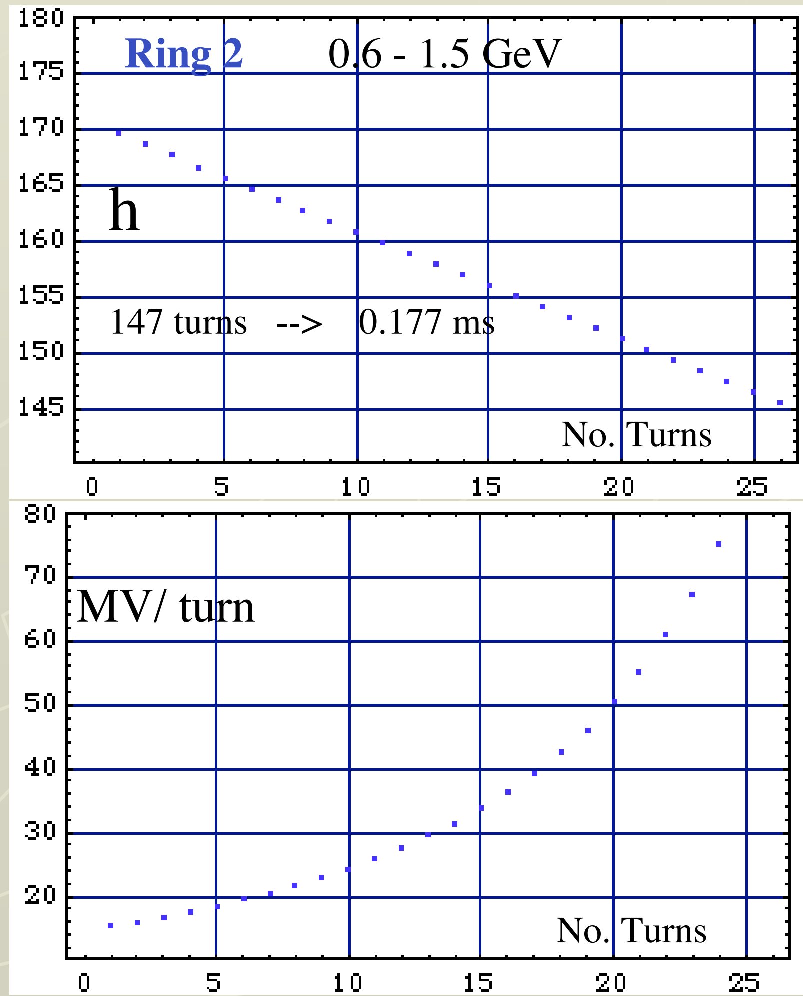


Constant RF **201.25 MHz**

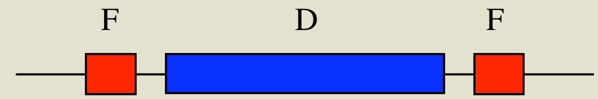
$$\Delta f / f = (1/\gamma^2 - \alpha_p)\,\Delta p / p \quad = -\,\Delta T / T \;=\; 1/h$$

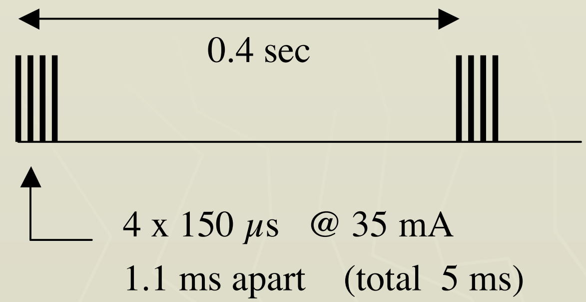
$$eV = E_0\, \beta^2 \gamma^3 / h\, (1 - \alpha_p \gamma^2)$$

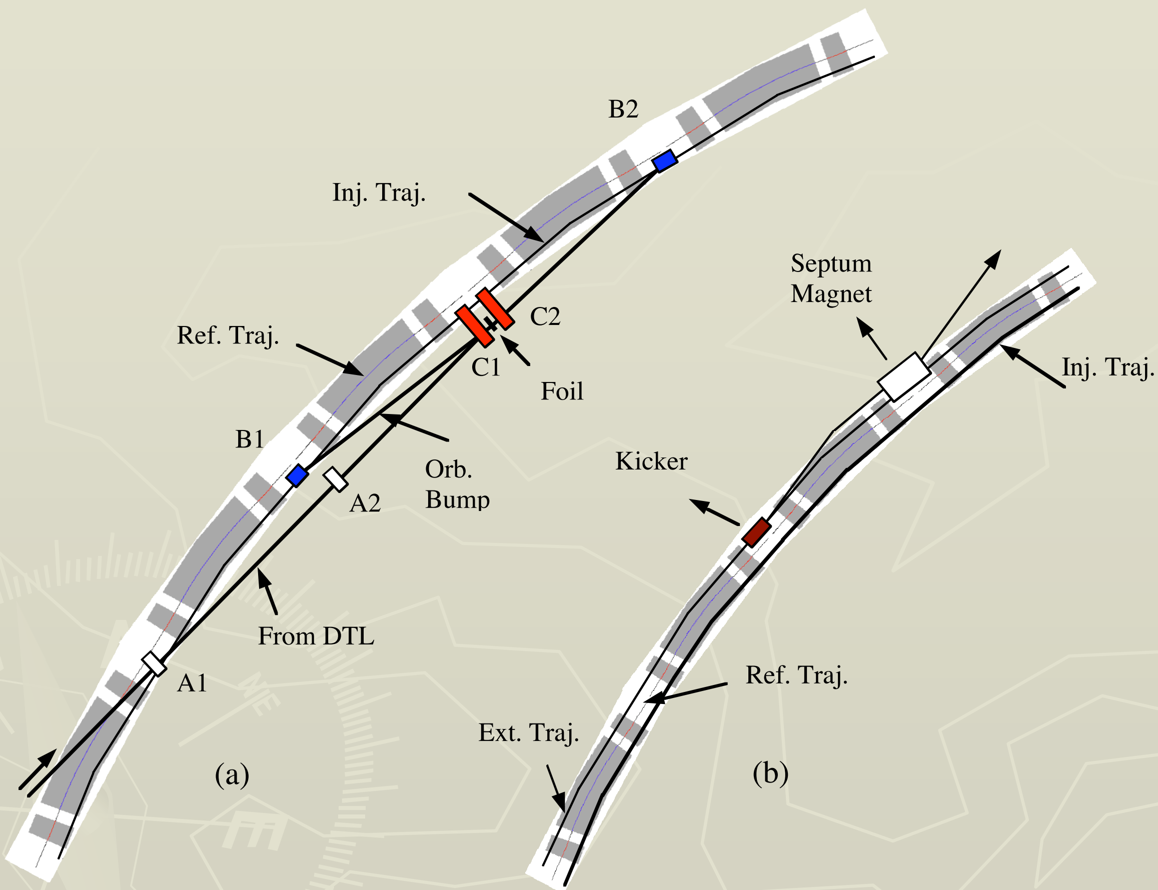




Injection (H^-) & Extraction

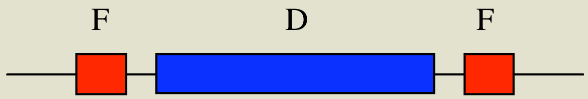






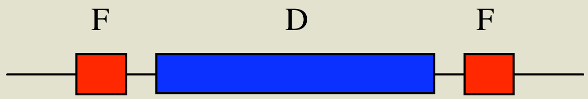
Linac Peak Current	35 mA
Rev. Period	1.44 μs
No. Protons / pulse	2.5 x 10^{13}
Chopping Ratio	80 %
Chopping Frequency	0.694 MHz
Single Pulse Duration	144 μs
No. inj. Turns / pulse	100
Emittance, rms norm.	1 π mm mrad
Bunching Frequency	201.25 MHz
σ_p / p	0.1 %

What to do Next….



Injector Requirements. Beam Pulse Formation.
Injector - FFAG Transport. Matching.
Multi-Turn Injection (H^-, Charge Exchange).
Single-Turn Extraction. Transport and Matching to AGS.
RF Capture in the AGS.
Space-Charge Limitation at Injection.
Control of Beam Losses: Halo Formation, Activation….
Instabilities…
Interaction with Residual Vacuum Gas.
RF Acceleration: *Frequency* vs. *Amplitude* Modulation
Beam Loading
Two Rings versus One Ring.
Transfer between Rings. Matching.
Acceleration of Heavy Ions (!?)
Magnet Design and Manufacture.
Beam Control, Diagnostic, Steering,…
Tune Control. Resonance Crossing.
Beam Abort, Dump.
Computer Tracking. Analytical Work. MATHEMATICA
Cost Estimate

Conclusions

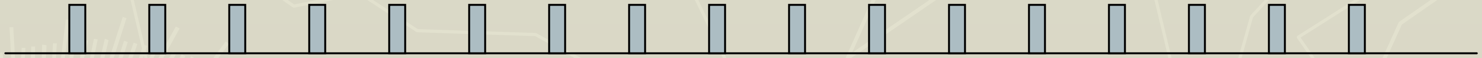


We have done a considerable amount of work.

We have launched new concepts and ideas.

We have made few inventions.

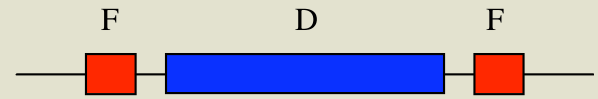
We need now to protect our Work….!



By extrapolation, it is also a continuous high power **Proton Driver** for a variety of applications:

Final Energy	1.5 GeV
Repetition Rate	670 Hz
Protons / Pulse	2.5×10^{13}
Average Beam Power	**4.0 MWatt**

Acceleration of Heavy Ions



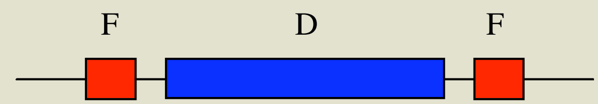
Protons

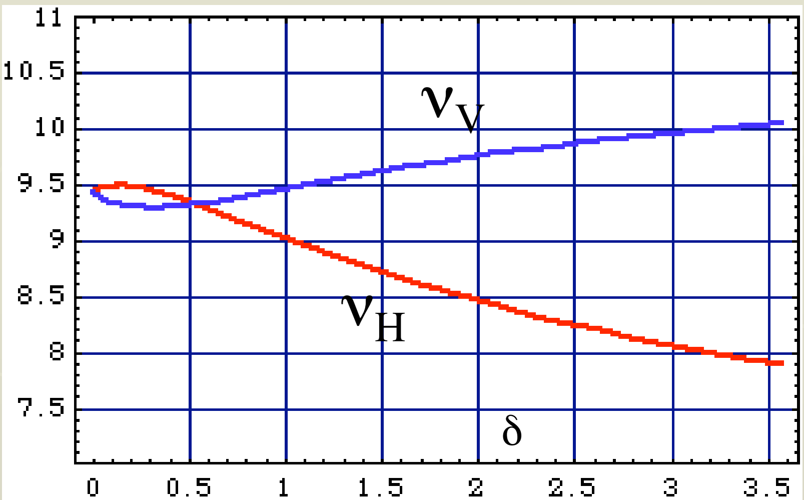
Kinetic Energy, MeV	200	600	1,500
β	0.56616	0.79244	0.92300
γ	1.21316	1.63948	2.59870
p, MeV/c	644.44	1,218.98	2,250.51
$B\rho$, kG-m	21.496	40.661	75.069

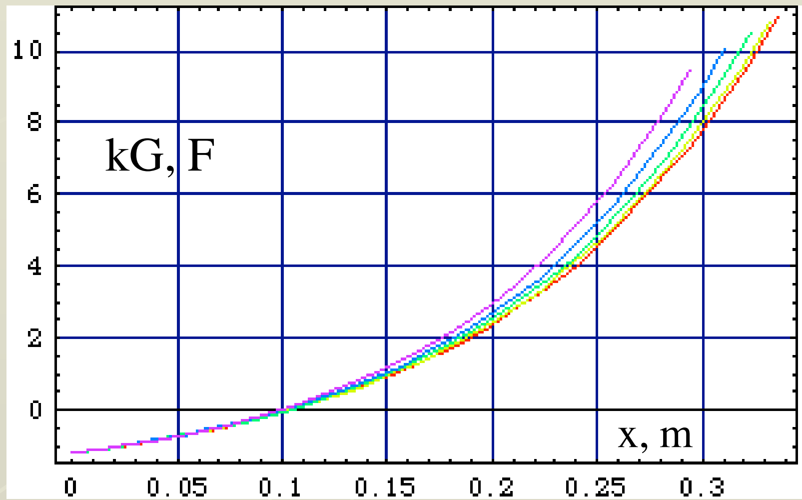
Gold Ions (Au) A = 197 Z = 79 Q = +33

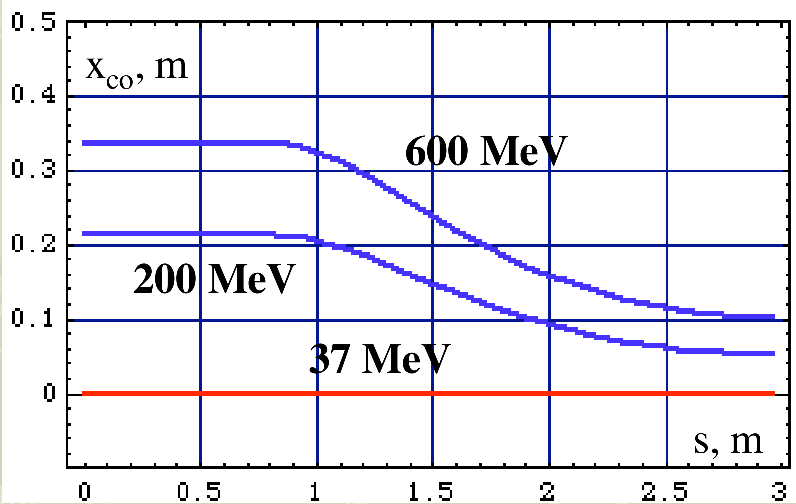
Kinetic Energy, MeV	1.066	22	350
β	0.04781	0.21360	0.68682
γ	1.00114	1.02362	1.37583
p, MeV/c	44.57	203.62	879.99
$B\rho$, kG-m	8.875	40.55	175.23

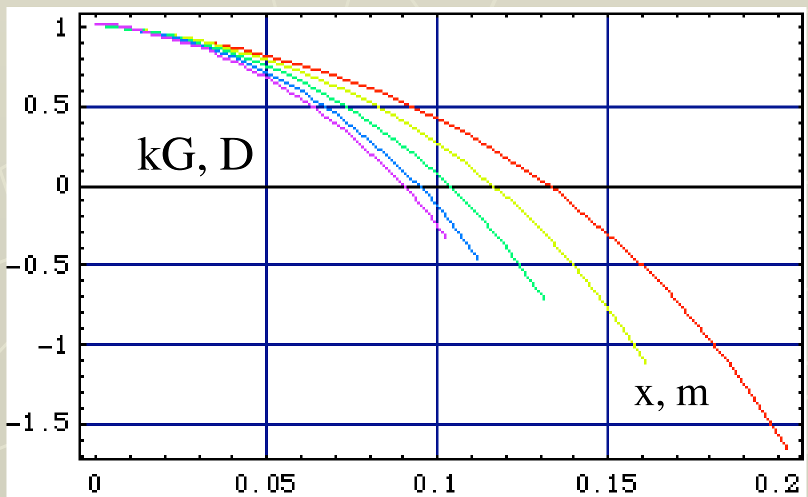
Heavy Ions -- Ring 1











Heavy Ions -- Ring 2